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MEASUREMENT OF NATURAL DRAFT

RESEARCH REPORT
OF THE COLLEGE OF ENGINEERING
THE PENNSYLVANIA STATE UNIVERSITY
UNIVERSITY PARK, PENNSYLVANIA
1964
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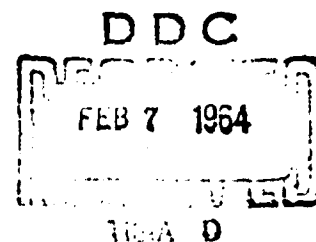
MEASUREMENT OF NATURAL DRAFT

a research project conducted by

THE COLLEGE OF ENGINEERING
THE PENNSYLVANIA STATE UNIVERSITY
UNIVERSITY PARK, PENNSYLVANIA

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ABSTRACT

Various methods for determining air change rates in a building space are critically investigated, and positive conclusions are drawn from the data. Several buildings are used for the determination of air change rates in potential shelter spaces by gravity circulation alone. The buildings vary in size, use and configuration, and air circulation paths are changed in each building in an effort to determine optimum conditions for gravity ventilation. An experimental test facility is used to check out and refine instrumentation, equipment, and procedures.

PREFACE

The ventilation of a shelter is one of the major items of cost, particularly when existing spaces are modified for use as shelters. It is recognized from the basic physics of air movement that heat in occupied spaces, under certain building configurations and with the advantage of common vertical ducts, offers opportunity for a certain amount of natural circulation. Therefore, if sufficient quantities of fresh air entered a space by natural means, the problem of ventilating that space in case of power failure would be reduced considerably. It would also be possible to eliminate expensive filtration equipment which is normally needed when a mechanical system with high velocity intake is provided.

The current shelter incentive program and the current shelter program which the federal government is funding will have a significant amount of effort devoted to the ventilation problem. The Office of Civil Defense is therefore deeply interested in getting answers to the ventilation problem.

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CHAPTER 1

INTRODUCTION

BACKGROUND

Much information relating to the need of human beings for specific conditions of the atmosphere has been accumulated over the years. These conditions involve temperature, humidity, air movement, oxygen, carbon dioxide and other gaseous content, as well as the inter-dependence of those factors. The tolerance ranges for these conditions have been determined for various levels of comfort and for many occupancy conditions. However, tolerability or the consequences of prolonged exposure to environmental extremes outside of the "comfort zone" have not been precisely defined, particularly with respect to the effects of age and state of health.

There is also a considerable amount of information available relating to the methods by which ambient temperature, humidity, air movement, and gaseous content are controlled. These methods apply to both open and closed spaces, and involve both regenerative and non-regenerative systems. Information concerning the effect which humans, animals, equipment and machines produce on the environment is also available.

In practically all of the pertinent literature, in all of the controlled experimentation, and in all of the published criteria dealing with protective shelters

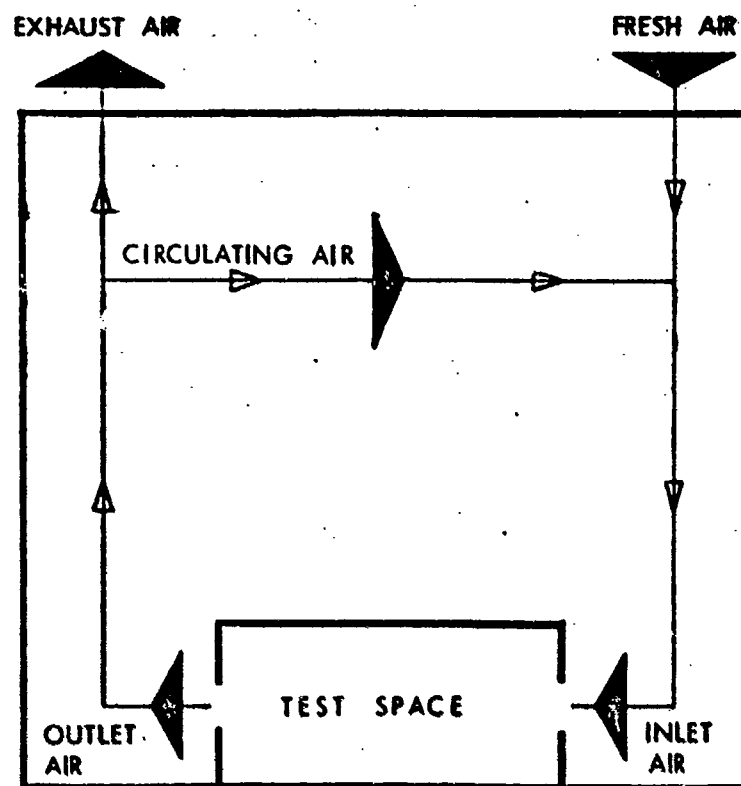
up to this time, the need for fresh air has been satisfied by bringing that air in from outside the building. (Figure 1 clarifies air flow terminology used in this report.) This has created a number of problems which have required ingenious, costly, and sometimes undesirable solutions. In order to exclude contaminated particles from a fallout shelter, for example, it is frequently necessary to provide screens, protection boxes, special intake terminals and/or filters. Filters, in turn, have created special problems of space, shielding, replacement, and disposal. Power equipment, in addition to being costly, also imposes a heavy load on the ventilation system for its own air supply and exhaust, and cooling requirements.

OBJECTIVES

The purpose of this study is to consider natural ventilation systems in certain protected spaces in selected buildings. The project objectives are: one, to develop reliable techniques for measuring the natural influx of fresh and inlet air to large shelter spaces; two, to make pilot studies of natural ventilation phenomena in typical spaces designated for shelter use in existing structures; and three, to investigate practical means of improving ventilation.

SCOPE

The project is keyed into the current shelter identification system and the shelter survey program, whereby a shelter space must have at least a potential occupancy of 50 persons to qualify as a community shelter, such to be marked and stocked by the federal government for that occupancy. The space will have a floor area of at least 500 square feet. This specific project is limited,



SCHEMATIC DIAGRAM OF AIR FLOW CIRCUIT

Definition of Terms:

- INLET AIR** - any air which enters the test space at the inlet.
- OUTLET AIR** - air ejected from the test space at the outlet.
- FRESH AIR** - air entering the building from the outside.
- EXHAUST AIR** - air ejected from the building to the outside.
- CIRCULATING AIR** - any flow of air within the building.

Figure 1

generally, to multi-story buildings because of the enhanced potential for effective shelters against fallout in such existing spaces. The natural ventilation of an isolated or a typical underground single-purpose shelter will not be considered. The problem is complicated by the fact that the space must be studied in relation to the total building system and to the usual labyrinth of vertical ducts.

CLIMATIC RANGES

All work was conducted on the campus of The Pennsylvania State University, located in the rolling hills of central Pennsylvania (Borough of State College, Pennsylvania), at approximately 41° north latitude. Tests were conducted during the spring and summer months while outdoor temperatures ranged between 45 F and 85 F.

GENERAL WORK SCHEDULE

Within the time available, a limited variety of building situations was investigated. In every case, the essential ingredient was a space which would serve adequately as a community shelter with a minimum of alterations or modification.

Considerable time was allocated in the first test building for developing a workable procedure and for checking out test equipment. Once that process had been refined and settled, the time spent in an actual test series could then be limited to two or three weeks. Some of the buildings considered were suitable for two or more series of tests with changed conditions each

time, while others were of such simple arrangement that a single series of tests would suffice.

The first test building used was a high rise dormitory (Building No. 1), a complete description of which is given in Chapter 3.

The next building (Building No. 2) was a three-story classroom-laboratory-office building with a full basement and a partial sub-basement. The sub-basement was used for the test space. A full description of this building is contained in Chapter 4.

The third building (Building No. 3) was another dormitory of 5 stories plus basement with a potential shelter space in the basement quite different from that in Building No. 1. This building was unoccupied during the summer, and therefore, was used for a variety of tests without interference of people, extraneous ventilation or artificial heat. Also, warm summer conditions reduced the air density difference of the stacks which resulted in a reduction of air circulation. For these reasons, the results of experiments in this building were more dependable and more meaningful than those gained from Building No. 1. A complete description of Building No. 3 is contained in Chapter 5.

BASIC PROCEDURES

The problem was essentially that of moving a mass of air through a space without benefit of mechanical equipment. The test spaces used in the project, which happened to be all below ground, were selected by virtue of

their sheltering properties. Occupants in a space will generate heat and moisture, and the heat can be utilized to provide the circulation to ventilate that space. It was, therefore, simply a matter of providing a path for air to flow from the test space to the remaining volume of the building and to permit the heat, humidity and carbon dioxide to be dissipated. Air from the larger volume could then recirculate to the test space. This is essentially a closed circuit, but it is recognized that normal infiltration into the building will occur through the cracks in windows and door assemblies, and to a very minor degree, through the wall construction. The quantity and probable consequences of radioactive particles entering these cracks through infiltration is a subject that needs further study. Cracks around pipes, ducts, partition walls and extraneous vents within the test spaces were sealed in order that more accurate results could be obtained for stack effects under controlled conditions.

The selected test spaces were equipped and instrumented to simulate occupants. A criterion of ten square feet per person was generally used so that a test space of approximately 1000 square feet would accommodate 100 persons. Heat was generated and dispersed within the room on this basis.

CHAPTER 2

INSTRUMENTATION AND EQUIPMENT

ENERGY INPUT TO THE TEST SPACE

1. Sensible heat:

For sensible heat input, banks of 100 and 200 watt lamps were used. These provided heat at the rate of 150 to 200 Btu's per person per hour as needed, the amount being varied as the room conditions changed and as an individual would vary his heat dissipation between latent and sensible. Basis for this distribution is available in an article by Achenbach, Phillips and Drapeau¹, with a summary given in Table 1 which follows.

Each bank of lamps (Figure 2) had a potential output of 3000 Btu's per hour. In order to avoid high intensity point sources the lamps were shielded with reflective aluminum covers and the entire bank enclosed within a perforated aluminum screen. The banks were quite evenly distributed around the test space to simulate the dispersion of occupants.

The power to operate the 120 volt single phase lamps was metered. Also, all other electrical equipment which added to the sensible heat load was metered.

1. Achenbach, P. R., Phillips, C. W., Drapeau, F. J. J.: ENVIRONMENTAL CHARACTERISTICS OF A SMALL UNDERGROUND FALLOUT SHELTER. ASHRAE Journal, Vol. 4, No. 1, pp 21-28, Jan. 1962.

Table 1 <u>NORMAL HEAT DISSIPATION IN BTU</u> <u>PER PERSON PER HOUR</u>			
SHELTER TEMP., DEGREES F	SENSIBLE HEAT	LATENT HEAT	TOTAL
70	300	100	400
75	250	150	400
80	200	200	400
85	150	250	400
90	100	300	400
From ASHRAE JOURNAL Vol. 4, No. 1, Jan., 1962.			

2. Latent heat:

Moisture was added to the test space by evaporating water from barrels placed in the room. A 55 gallon barrel was filled with city water and placed on an elevated platform mounted on a platform scale. The water was weighed and then fed as required to humidifier barrels, one of which is illustrated (Figure 3). The water level was held constant in those barrels by float-operated feed water valves. Immersion type resistance heaters were used to evaporate the water. Power to operate the heaters was metered and recorded.

The weight of the 55 gallon water supply drum was recorded before and after the addition of water. By this means, it was possible to keep a record of the amount of water evaporated per hour and the energy required to accomplish the evaporation. From the collected data, it was then possible to calculate the quantity of latent heat supplied to the test space.

TEMPERATURE MEASUREMENT

Air temperatures were measured by means of copper-constantan thermocouples. These were connected to a recording potentiometer (Figure 4) which measured and recorded the entering air, room air, and leaving air temperatures every hour. Surface temperatures for walls, ceiling and floor were measured and recorded every hour by means of another potentiometer circuit.

HUMIDITY MEASUREMENT

1. Automatic psychrometers

A specially constructed automatic psychrometer (Figure 5) measured and recorded on the air temperature potentiometer, the dry bulb and wet bulb temperatures at inlet and outlet to the test space. These measurements were made once each hour. The relative humidity and moisture gain in the room were then determined with the aid of a psychrometric chart.

2. Hygro-thermographs

Hygro-thermographs (Figure 6) were placed at the entrance and exit of the test space in order to obtain a general and continuous record of the inlet and outlet air temperatures and humidities.

EFFECTIVE TEMPERATURE

When temperature and humidity readings indicated steady-state internal conditions, it was considered that thermal equilibrium had been established. The upper effective temperature limit was arbitrarily set at 85 F on the basis of existing data from controlled experiments (Refer to Reference 7 in the bibliography). This permitted a variation of wet bulb and dry bulb conditions. For example, if the dry bulb were limited to 90 F, the wet bulb would be limited to 82 F under a practically static air movement of 20 feet per minute (Figure 7). The relative humidity at this condition would be 80%.

WEATHER DATA

Weather data available from the University Weather Station, located within a mile from all test buildings, includes the followings:

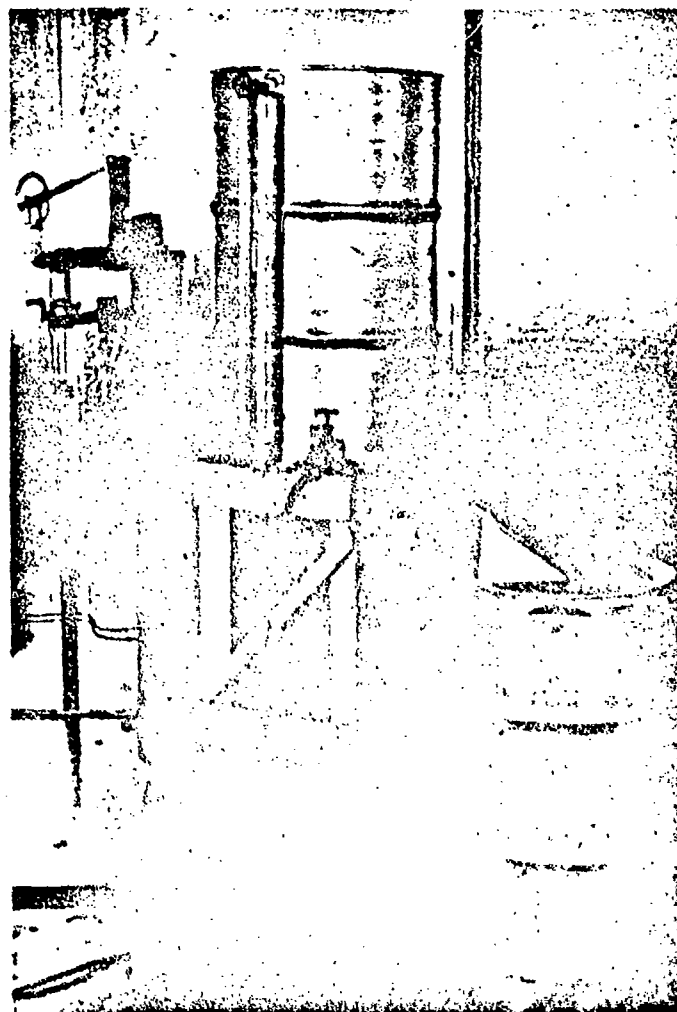
- a. Ambient temperature
- b. Wind velocity
- c. Wind direction
- d. General weather conditions, i.e., rain, cloudy, etc.
- e. Total solar radiation
- f. Precipitation
- g. Relative humidity

This data was obtained as needed for the various tests. An attempt was made to find some correlation between outside weather conditions and changes in internal conditions within the test spaces. If such a correlation does exist, it is not apparent in the limited but varied tests conducted in



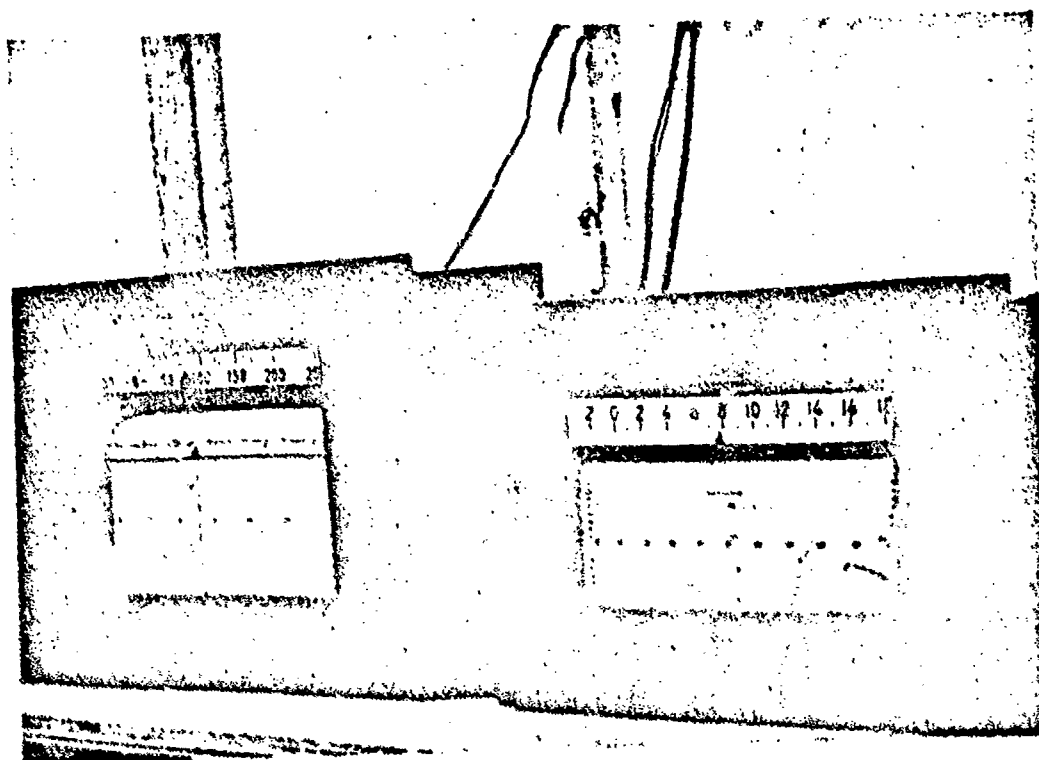
LAMP BANK

Figure 2



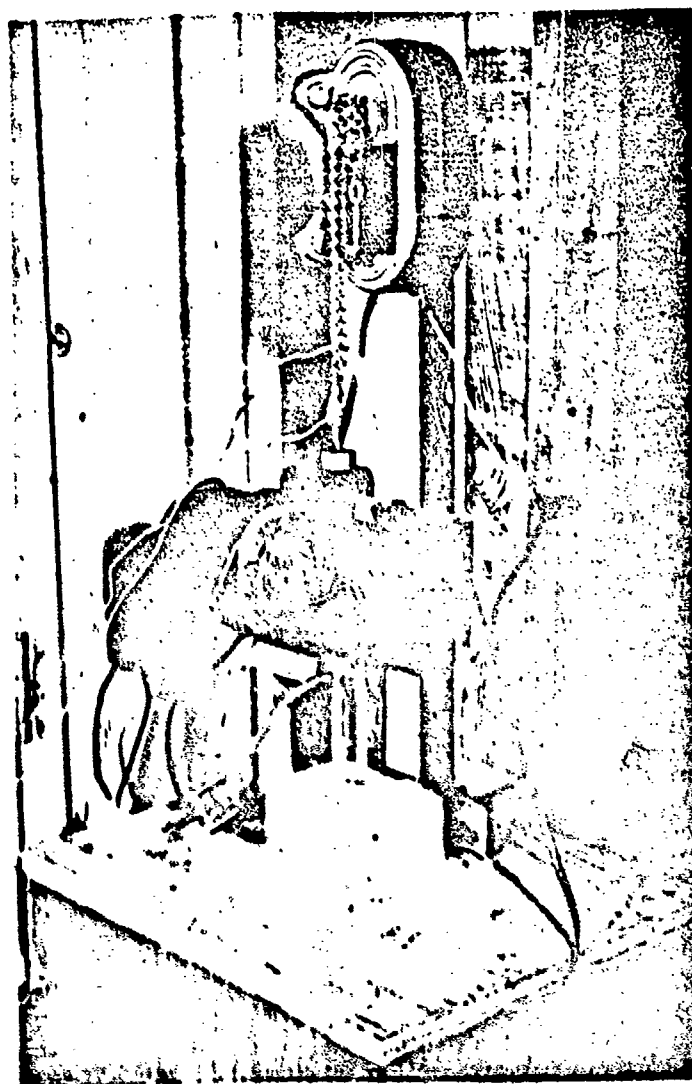
HUMIDIFIER BARREL

Figure 3



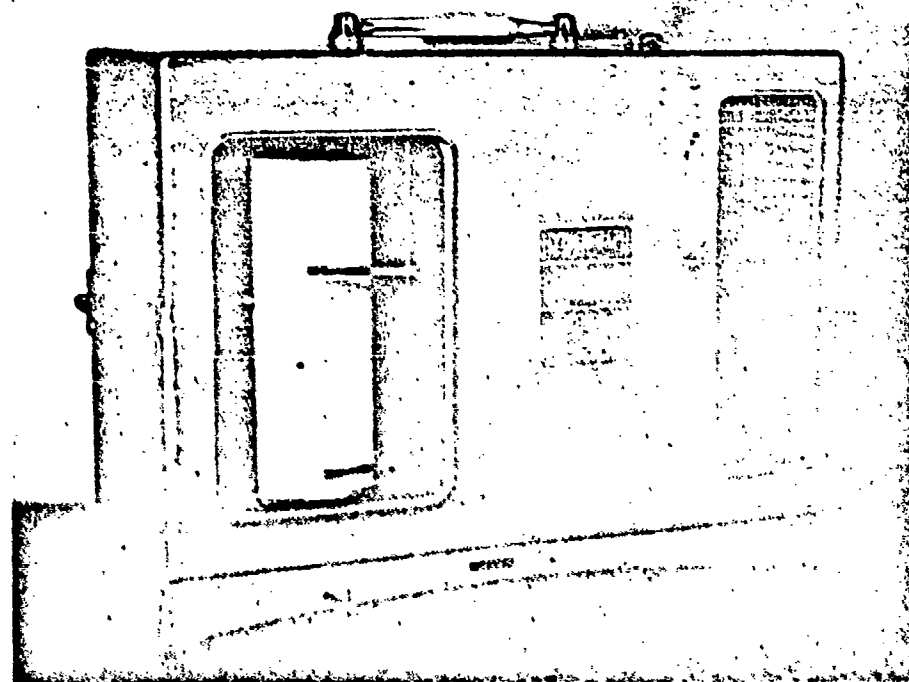
RECORDING POTENTIOMETERS

Figure 4



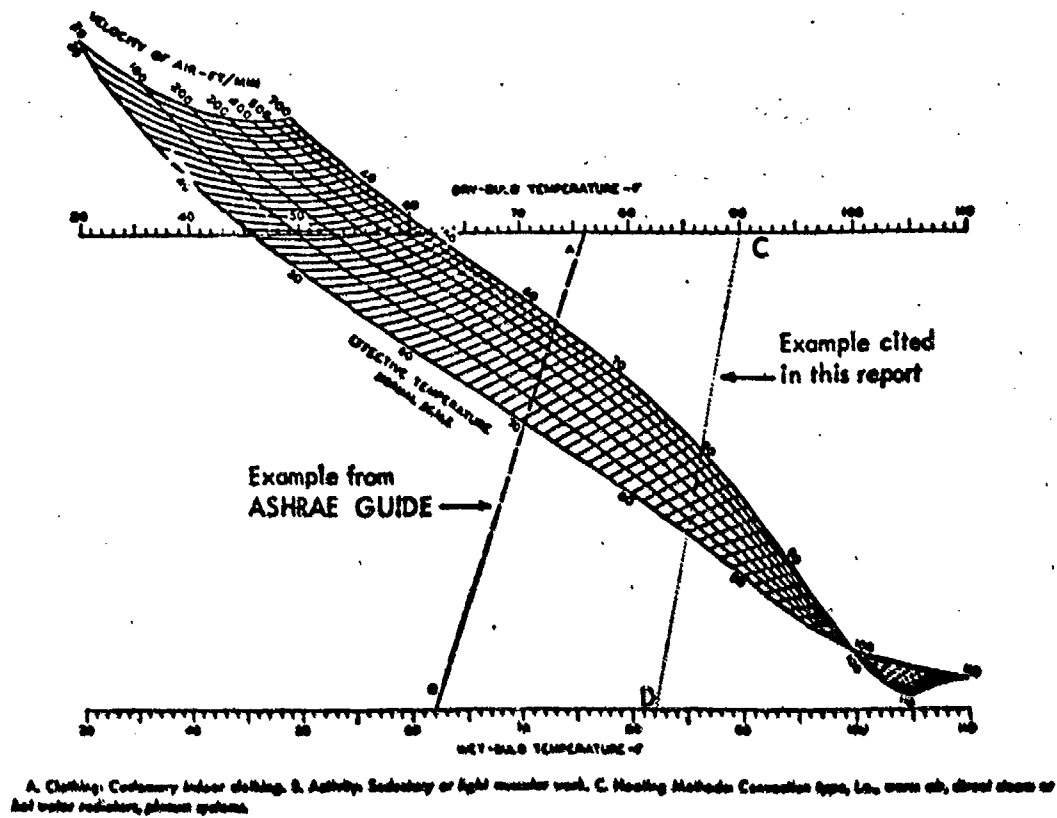
AUTOMATIC PSYCHROMETER

Figure 5



HYGRO-THERMOGRAPH

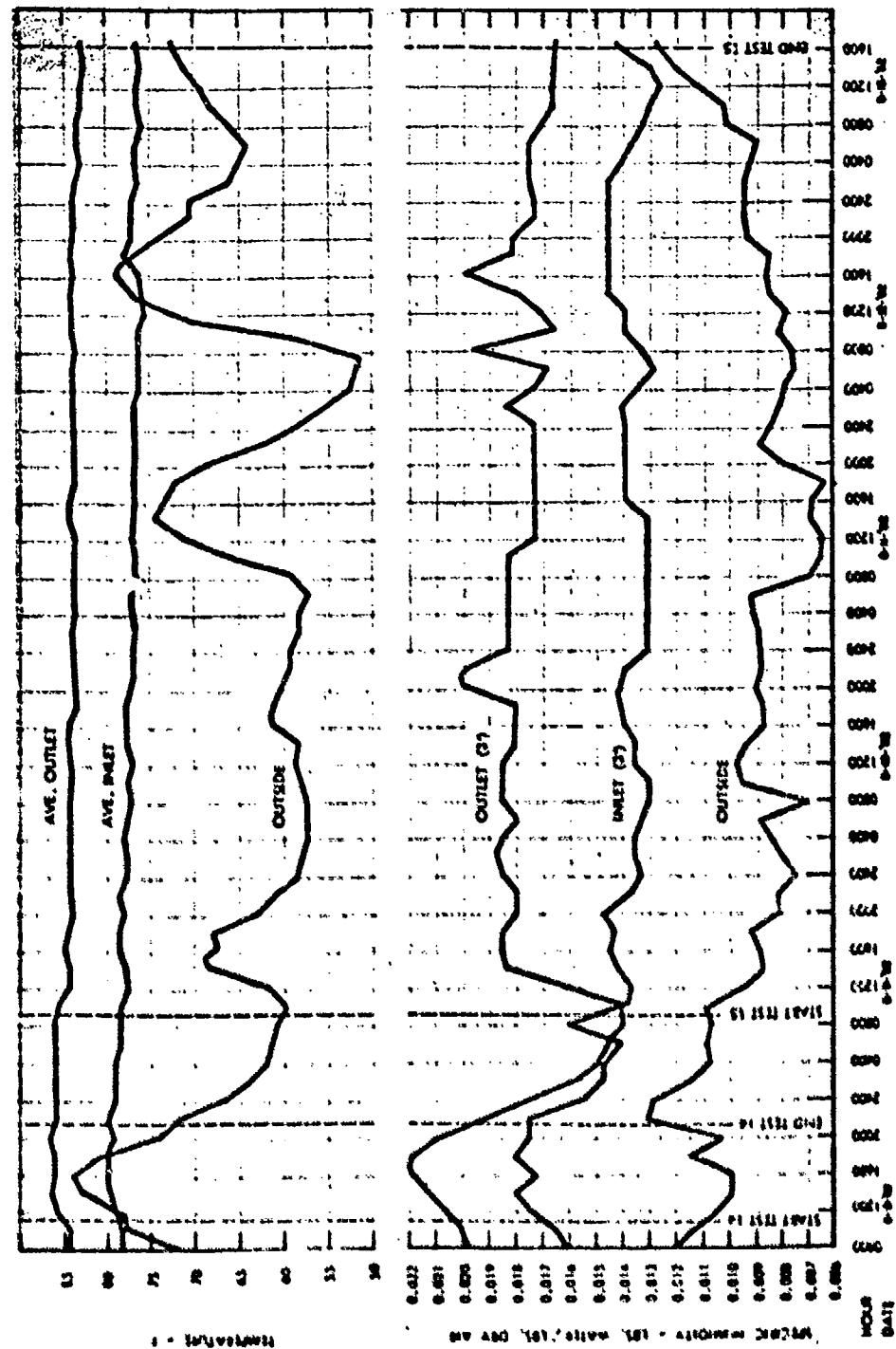
Figure 6



(from ASHRAE GUIDE for 1961, p. 109)

EFFECTIVE TEMPERATURE CHART

Figure 7



OUTDOOR-INDOOR ENVIRONMENT COMPARISONS - BUILDING NO. 3

Figure 8

this research project. An explanation can be found, perhaps, in the fact that the time available did not permit an extensive series of tests in any one building with changes of only one of the numerous variables. A typical plot of external-internal environmental conditions (Figure 8) shows a general lack of correlation.

METHODS OF MEASURING AIR CHANGE RATES

1. TRACER GAS DECAY METHODS

General principles of tracer gas technique:

The air change rate of an enclosure is defined as the ratio of the hourly rate at which air enters (or leaves) the enclosure to the volume of the enclosure. Equipment which uses the tracer gas technique was employed in many tests on this project to determine the air change rate.

The amount of decay in tracer gas concentration in the test space per unit time is numerically equal to the amount of tracer gas leaving the space with the outlet air in the same unit time. This can be expressed by the formula:

$$-VdC = NVCdt \quad (1)$$

where V = Volume of the space, cubic feet
 C = Concentration of tracer gas at time t , ppm
 N = Number of air changes per hour
 t = Time, hours

with $C = C_0$ at $t = 0$, the solution of equation (1) is:

$$N = \ln [C_0/C] / t \quad (2)$$

Equation (2) states that the number of air changes occurring during time t is equal to the natural logarithm of the ratio of the initial tracer gas concen-

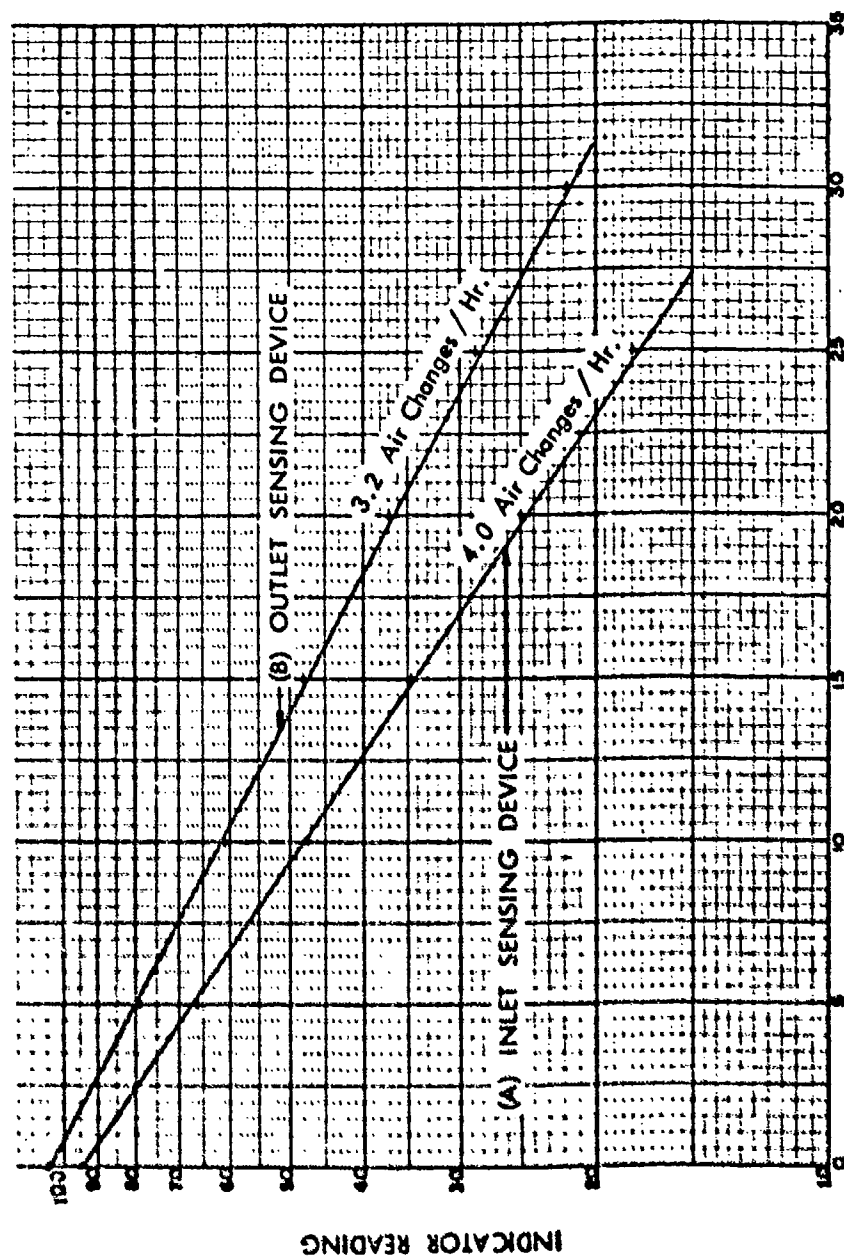
tration to the concentration at the end of the time interval. The rate of ventilation can then be calculated by multiplication of V , the volume of the space, and N , the number of air changes per hour. Typical decay curves are illustrated (Figure 9).

The main function of any equipment used in employing the tracer gas decay method of determining air change rate is to indicate the concentration of the tracer gas in the test space as a function of time. There are many methods available for obtaining this result and several of the best methods were employed during the various tests in this project. In general, the toxicity of the gases suggested for use in this work can be ignored, except for the simple but important precaution of preventing any contact of Freon with hot plates, boilers and other high temperature surfaces.

A. PORTABLE INFILTRATION METER

1. General information:

The basic tracer gas equipment used for this project was a Portable Infiltration Meter on loan from the National Bureau of Standards where it was developed by Mr. Carl W. Coblenz, Mechanical Engineer. The Portable Infiltration Meter utilizes the change in thermal conductivity of the mixture of air and tracer gas as the method of measuring the change in tracer gas concentration. Helium serves as a very satisfactory tracer gas since its thermal conductivity is six times that of air, and a small change of concentration of helium in air causes a readily detectable change in thermal conductivity.



TIME - MINUTES
 TRACER GAS DECAY CURVES (HELIUM)

Figure 9

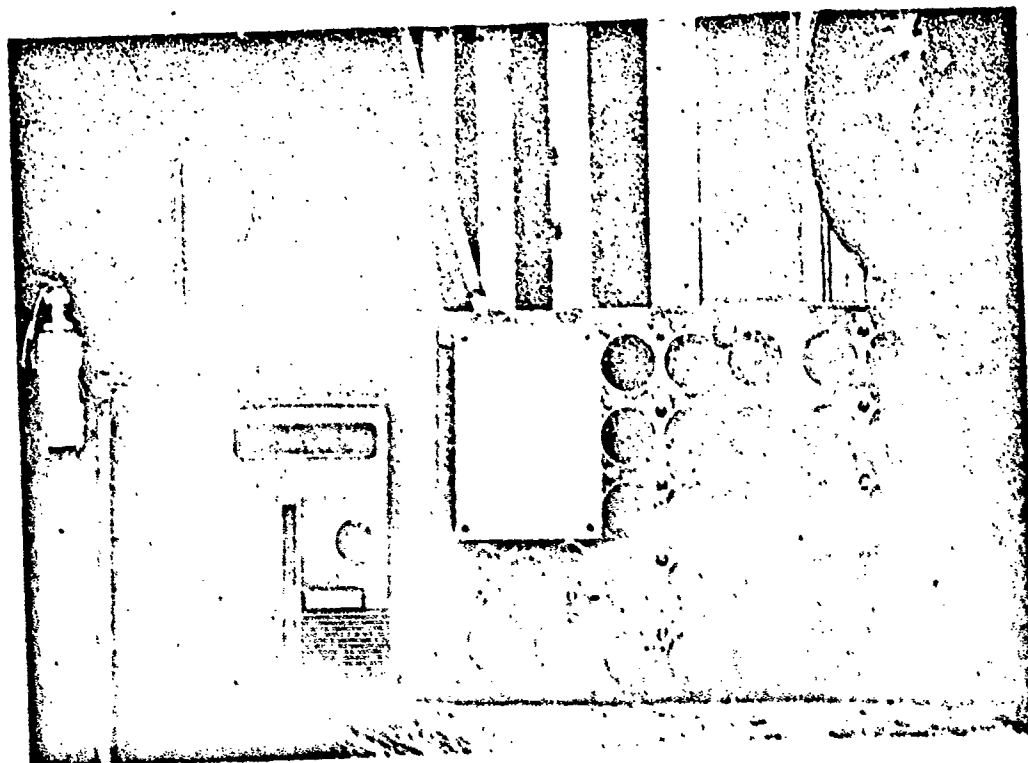
2. Sensing devices:

A sensing device, shown with control cabinet (Figure 10), is a small aluminum cylinder with two 5/8 inch i.d. cavities symmetrically arranged. Carefully matched thermistors of the bead type on a glass probe are enclosed in the cavities. One cavity is hermetically sealed while the other has 3/64 inch holes at the top and bottom of the cavity to permit natural convection air movement induced by the heated thermistor. A schematic cross section of such a sensing device is also shown (Figure 11).

Because of the higher conductivity of helium, heat transfer by conduction is greater in the cavity which contains the helium air mixture. When the sensing device is heated, the thermistor in the helium air cavity will be slightly cooler than that in the sealed cavity. Since small changes in temperature produce a considerable change in the thermistor resistance, a change of helium concentration can be determined by observing a difference of the resistance of the two thermistors. By installing the two thermistors in a Wheatstone Bridge circuit, the unbalanced resistance can be used as a measure of helium concentration.

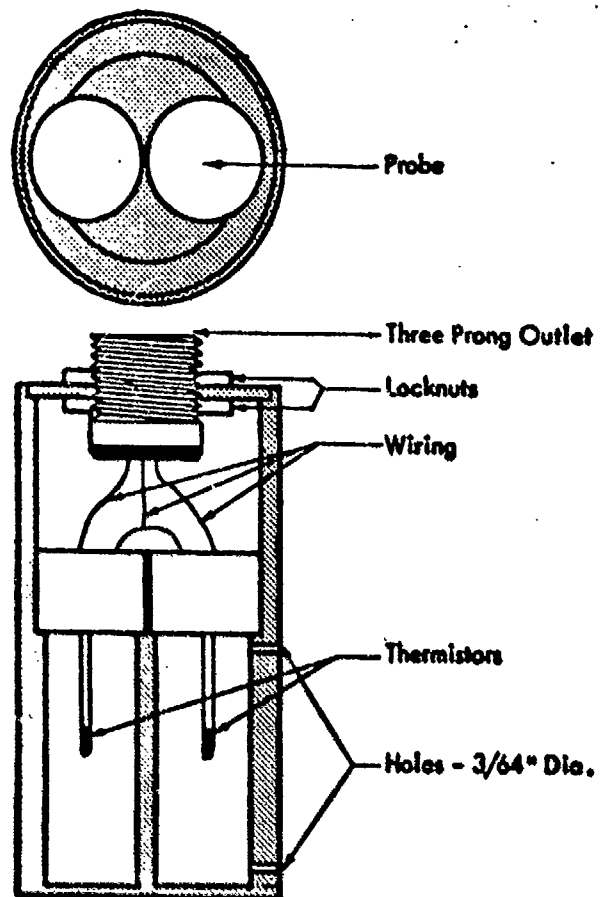
3. Measuring apparatus:

The control cabinet housing the bridge circuits and control equipment for the sensing devices (Figure 10) operates on a 115 volt a-c power supply. A schematic wiring diagram of the apparatus, showing the power supply and metering circuit and one of the ten sensing device circuits is also shown (Figure 12).



THE N. B. S. PORTABLE INFILTRATION METER —
SENSING DEVICE, INDICATOR, AND CONTROL CABINET

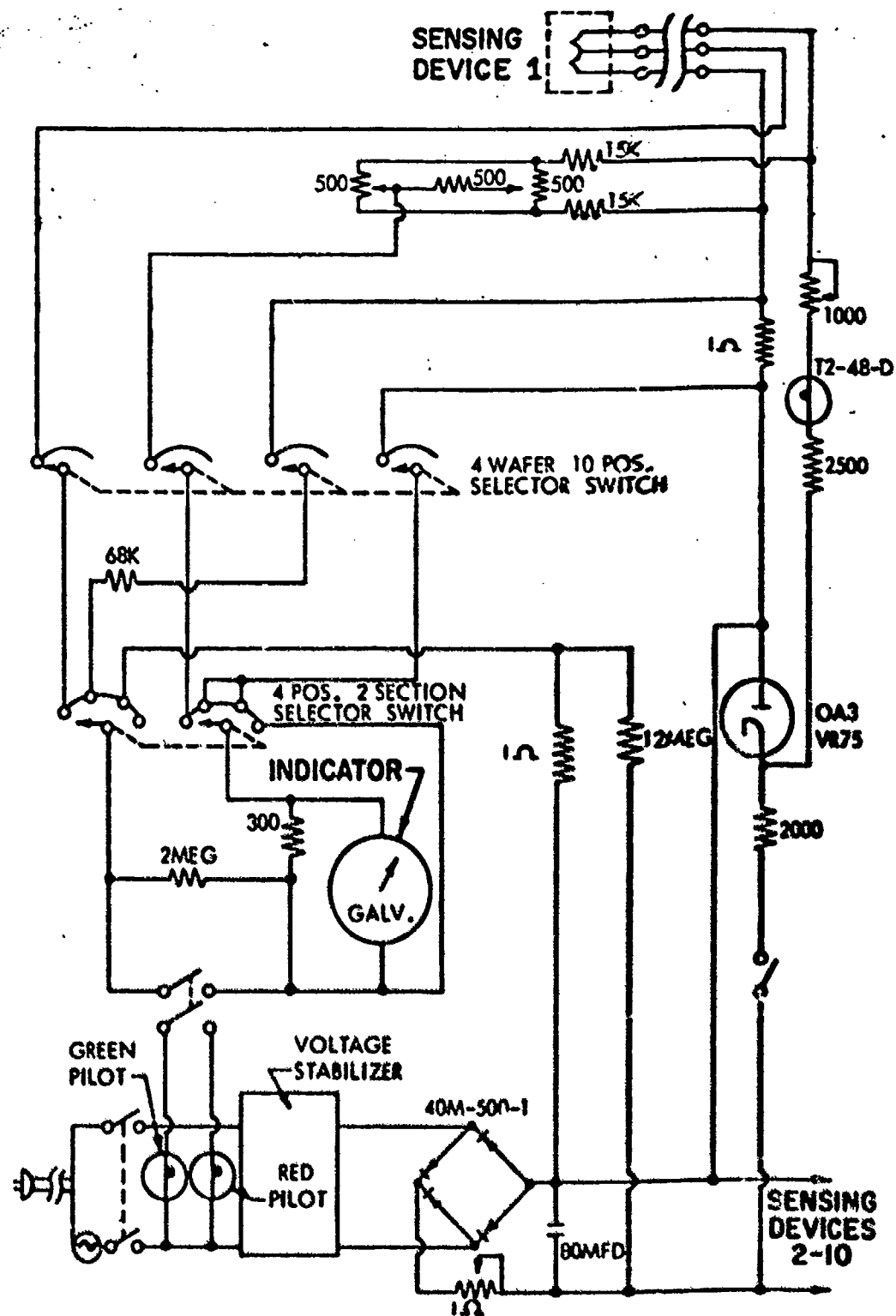
Figure 10



SECTION THROUGH SENSING DEVICE

Scale: full size

Figure 11



SCHEMATIC WIRING DIAGRAM FOR PORTABLE INFILTRATION METER

Figure 12

Two 15K ohm resistors form the fixed legs of the Wheatstone Bridge for each sensing device. Each bridge circuit is balanced with two 500 ohm variable resistors connected in parallel. One of them is connected in series with a fixed 500 ohm resistor to provide a coarse and a fine adjustment over a wide range. A filtered 105 volt d-c supply for each sensing device circuit is obtained by using a voltage stabilizer and a full-wave selenium rectifier.

A constant wattage network is required for supplying the thermistors. Line voltage fluctuations are reduced by means of a voltage regulator tube OA3-VR75. With a 1000 ohm variable resistor and a switchboard bulb T2-48-0 operating as voltage dropping resistors, changes in the bridge heater current are held to a minimum.

A Leeds and Northrup galvanometer with a full scale deflection of 0.5 micro-amperes current serves as an indicator. Two series-connected-selector switches and the necessary shunt and voltage-dropping resistors permit the measurement of the progressive unbalance of the Wheatstone Bridge circuit of each sensing device. This also permits measurement of the d-c output voltage of the rectifier, the heating current of each sensing device, and it allows shunting of the indicator when not in operation.

4. Operational procedure:

For air change rate measurements, the control cabinet is generally placed outside the test space while the sensing devices are mounted at selected locations within the space. The heating current of each sensing device is

adjusted and all components are allowed to warm up to a steady-state condition. The bridge circuit is then balanced by adjusting the balancing resistors so that the indicator reads zero for each sensing device used in the test.

Helium in the amount of 0.6 percent of the total volume of the test space is introduced into the space and thoroughly mixed with the air by means of desk type fans. The progressive unbalance of the Wheatstone Bridge circuit of each sensing device is then plotted on the semi-logarithmic paper and the air change rate calculated by the use of equation (2).

5. Advantages of the Portable Infiltration Meters

- a. Ready availability of equipment and gas to the researchers on this project.
- b. Relative convenience for use in an occupied building without causing discomfort or even awareness to the occupants.
- c. Relatively easy to operate.

Disadvantages of the Portable Infiltration Meters

- a. Non-recording, therefore requires manual manipulation.
- b. Requires a minimum of 30 minutes to observe decay of one charge of helium after it has been introduced into the test space.
- c. Becomes inoperative at high humidities.
- d. Unsuitable for air change rates higher than 3 changes per hour.

- e. Only a limited number of checks can be made of the air change rate during a given test period because of the necessity of allowing the test space air to become completely free of helium content between tests.
- f. Each sensing device detects a decay rate only in the immediate vicinity of the sensing device, making it difficult to ascertain average air change rate for a large and/or irregular test space.

6. Application of tracer gas decay methods to large and/or irregular spaces

When a test space is long and large with a single inlet and outlet, air moves through the space in an irregular pattern. There is a mixing of air by eddy currents superimposed on the flow toward the outlet. Therefore, sensing devices indicating tracer gas concentration placed at different locations in the test space will indicate substantially different air change rates. Suppose the tracer gas initially is uniformly mixed with the air in the test space and then air is permitted to flow through the space. Sensing devices near the inlet will indicate a much higher air change rate initially than will sensing devices near the outlet. This is due to clean air entering the test space and quickly mixing with the tracer-gas-laden air near the inlet thus causing a rapid decrease in the tracer gas content of this air at the same time. Near the outlet, all air reaching the sensing device will initially contain the same concentration of tracer gas as originally supplied to the test space. Also, any sensing devices located between the inlet and outlet will indicate air change rates that are between

these extremes. Thus, for large test spaces and fairly large air change rates, extreme difficulty is encountered in judging which sensing device is indicating the most nearly correct decay rate, and also what space this decay rate has surveyed. In Building No. 3 where the test space consisted of a large area at one end and a narrow corridor at the other, an attempt was made to minimize such problems in employment of this method by placing the sensing devices in the large area near the outlet and initially supplying only the air in this area with the tracer gas. However, regardless of the size and configuration of the test space, the tracer gas decay method becomes unreliable when the air change rate exceeds 3 changes per hour. This limit was exceeded in some tests, especially in Building No. 3, wherein other methods have proved their value.

B. WESTINGHOUSE ELECTRONEGATIVE GAS DETECTOR

1. General Information:

This instrument also employs tracer gas decay principles and therefore possesses advantages and disadvantages associated with this technique. The instrument is a portable leak detector developed by Westinghouse Research Laboratories for measuring small or trace quantities of electronegative gases, such as sulphur hexafluoride, SF_6 . Although the instrument was developed to leak-test enclosures for SF_6 -filled distribution apparatus, it is sensitive to many other gases and vapors, including common refrigerants and organic solvents. This instrument permits the absolute measurement of SF_6 in concentrations as small as 1 part per million of SF_6 in air, and can detect quantities as small as

one tenth part per million of SF_6 in air. Since the principle of operation depends on fundamental properties of the gases, its calibration and sensitivity are stable characteristics. Special techniques can be used to extend the range for SF_6 down to 0.1 ppm measurement and 0.02 ppm detection. This instrument recovers rapidly from excessive concentrations of the detected gas.

The Westinghouse Electronegative Gas Detector may be used to find leaks of SF_6 or of other electronegative gases by the search method, to measure the total leak rate of a device with the aid of an external enclosure, or to measure trace or substantial quantities of the gas in a given test space. As used to detect SF_6 , the instrument operates on a principle which makes use of the difference in mobility of SF_6 and O_2 ions, and of the large electron attachment coefficient of SF_6 compared to O_2 , to distinguish between SF_6 and oxygen in the test space air. Air from the test space is drawn in through the sensing device by a pump, passed through a dust filter and a humidistat, and passed on to the head, where an electrical signal is developed of which the a-c component has a phase dependent on the concentration of SF_6 in the test space air. The a-c signal is amplified, rectified in a phase-sensitive detector and the resulting d-c output indicated by a meter calibrated in ppm SF_6 in air. In addition to the indicator reading, a flashing light in the sensing device and a pulsed audio tone help to monitor the measured concentration. The repetition rate of the light and tone pulses is proportional to the indicator deflection, varying from one pulse per second at left scale to

10 pulses per second at right scale. The pulse rate goes to zero for a reverse, off-scale indication. These audio and visual monitors permit leak searching without continual reference to the indicator.

The relative detectability of various refrigerants, as compared to SF_6 , is shown in Table 2. In applications where it is possible to use a non-electro-negative gas such as N_2 for the background gas instead of air, increases in sensitivity as high as 1000-fold may be achieved.

Table 2
RELATIVE DETECTABILITY OF VARIOUS REFRIGERANTS

GAS	CONCENTRATION (IN PPM) TO GIVE INDICATION OF 1 PPM SF_6
Refrigerant 12* (CCl_2F_2)	30
Refrigerant 13 (CClF_3)	700
Refrigerant 14 (CF_4)	5,000
Refrigerant C 318 (C_4F_8)	0.8
Refrigerant 22 (CHClF_2)	70
Refrigerant 23 (C_4F_3)	60
Refrigerant 116 (CF_3CF_3)	1,000
Sulphur Hexafluoride (SF_6)	1

*Freon 12 (F-12) was the refrigerant used in this research project.

2. Operational procedures:

The Westinghouse Electronegative Gas Detector is placed in the test space and turned on. A suitable range is selected from those possible which are 2, 5, 10, 20, 50, and 100. Each number indicates the number of parts per million of sulphur hexafluoride (SF_6) that the instrument will detect. Because SF_6 was unavailable at the time of testing, Freon 12 was used. The scale number, therefore, had to be multiplied by 30. Thus, in using the 20 scale, 6000 parts per million of Freon 12 was introduced into the test space.

The instrument has an automatic zeroing mechanism and will zero itself before tracer gas is added to the test space. The tracer is then added and the concentration can be read directly on the indicator.

The initial charge of gas, Freon or SF_6 , which is added to the test space air will settle, since the gas is very heavy, unless the gas is thoroughly mixed with the air in the test space. This is done by using several desk type fans for homogenizing the air throughout the test space. This should be done very carefully.

Since the instrument is self-zeroing, it is necessary to have a supply of tracer-free air at test space temperature available at all times during the test, so that a continuous zero can be maintained, and the possibility of drift of the instrument eliminated.

C. MINE SAFETY APPLIANCES ANALYZER

The use of carbon dioxide as a tracer gas with an MSA Lira Infra-Red Analyzer has been considered. The instrument appears to be adequately sensitive. However, the background concentration of CO_2 is a variable, and a second instrument would be required to monitor the background concentration at the same time that observations were being made in the test space.

D. GE TYPE H-1 LEAK DETECTOR

Freon 12 has been used in other experiments as a tracer while using a GE Type H-1 Leak Detector to sense the presence of the Freon. Several problems exist. The instrument is not supplied with a concentration calibration, presumably because the instrument is not stable in this respect. It is quite sensitive, but the life of the sensing device is rather short when continuous duty is considered. Intermittent duty of several hours on and several hours off is recommended by the manufacturer. This instrument is not normally equipped with a recorder, although this should not be a major problem if the calibration could be stabilized.

Table 3 contains pertinent summary data for comparison of various tracer gas detectors.

Table 3

TRACER GAS DETECTORS

MAKE	TRACER	CONCENTRATION	TRACER COST/cu. ft.	INSTRUMENT COST	COST CHARGE 10,000 cu. ft.
National Bureau of Standards Portable Infiltration Meter	He	500 ppm full scale	\$.14	not available commercially	\$7.00
Westinghouse Electronegative Gas Detector	SF ₆	50 ppm full scale	\$1.20		\$.60
	F-12	1500 ppm full scale	\$.30	\$5850	\$4.50
Mine Safety Appliance Co. Gas Analyzer	CO ₂	2000 ppm full scale	\$.04	\$1385	\$.80
Two recorders required. Approximate cost: Approximate total cost with recorders:					
				\$2315 \$3700	
General Electric Type H-1 Leak Detector	F-12	300 ppm	\$.30	\$ 800	\$.90
Not stable to calibrate. Easily contaminated. Life - 1000 hrs. continuous duty.					

2. ALTERNATE TRACER GAS TECHNIQUES

The "decay" method for determining air change rates uses a slug of tracer gas to build up an initial concentration which can be monitored periodically as it decays under the action of air flow. The monitoring must be done manually and the observations plotted to obtain an average value of the air change rate during the period of observation.

Alternate methods of use could reduce the work involved and possibly yield a continuous record of air change rates. One method would be to add the tracer gas at a fixed rate and continuously record the concentration within the test space. Under this method the concentration of the gas would rise and fall under the influence of the air flow and air infiltration. With limit controls to avoid excessive concentrations this method should work satisfactorily. One of its disadvantages is the use of excessive quantities of tracer gas.

The high concentrations and excessive use of tracer gas can be avoided by controlling the rate at which the tracer gas is added to the test space to maintain a constant minimum concentration. The rate at which the gas is added is then a continuous measure of the air change rate. The advantages to this approach are that a minimum concentration and a minimum quantity of tracer gas is used, and the record of air change rate is virtually continuous. This equipment has not been assembled and its actual performance remains to be demonstrated.

The most promising combination appears to be the Westinghouse Electronegative Gas Detector with either Freon or sulphur hexafluoride as the tracer gas.

3. WATER VAPOR METHOD

The water vapor method is essentially the application of the law of conservation of mass to the test space. The mass to be considered is the water that is added to the test space as vapor in the simulation of latent heat addition.

A statement of this law is:

$$\begin{array}{c}
 \boxed{\begin{array}{l} \text{Water in Incoming Air} \\ \text{(lb/hour)} \end{array}} + \boxed{\begin{array}{l} \text{Water Added as Latent} \\ \text{Heat in Space (lb/hour)} \end{array}} = \\
 \boxed{\begin{array}{l} \text{Water in Leaving Air} \\ \text{(lb/hour)} \end{array}} + \boxed{\begin{array}{l} \text{Water Migrating} \\ \text{into Surfaces (lb/hour)} \end{array}}
 \end{array}$$

If the surfaces of the space are conditioned prior to testing by means of a suitable coating, migration into the surfaces will be small and can be neglected in the analysis.

The result of the analysis gives the following equation for calculating air change rate:

$$N = \frac{W \cdot V}{(\Delta H) V} \quad (3)$$

where N = Air change rate (air changes per hour).
 W = Rate of water addition to space (pounds per hour)
 V = Average specific volume of dry test space air (cubic feet per pound of dry air).

V = Volume (cubic feet per air change).

ΔH = Change in water content of air entering and leaving the space
(pounds of water vapor per pound of dry air).

Psychrometric readings are taken of inlet and outlet air. A Psychrometric Chart is used to determine the change in absolute humidity or water content of the air as it passes through the test space. The average specific volume of the air is also determined from the chart. Knowing the rate of water addition and the volume of the space, Equation (3) is used to determine air change rate.

SAMPLE CALCULATION:

Inlet Conditions

db = 77.0F

wb = 65.0F

H = 0.0105 lb/lb

Outlet Conditions

db = 87.0F

wb = 77.5F

H = 0.01825 lb/lb

$\Delta H = 0.01825 - 0.0105 = 0.00725$ lb of water vapor per lb. of dry air

$V = 14.0$ cubic feet per pound of dry air

$W = 9.0$ lb. of water added per hour

$V = 6,000$ cubic feet per air change

$$N = \frac{(9)(14)}{(0.00725)(6000)} = 2.7 \text{ air changes per hour}$$

The rate of ventilation can then be calculated by multiplication of V , the volume of the space, and N , the number of air changes per hour.

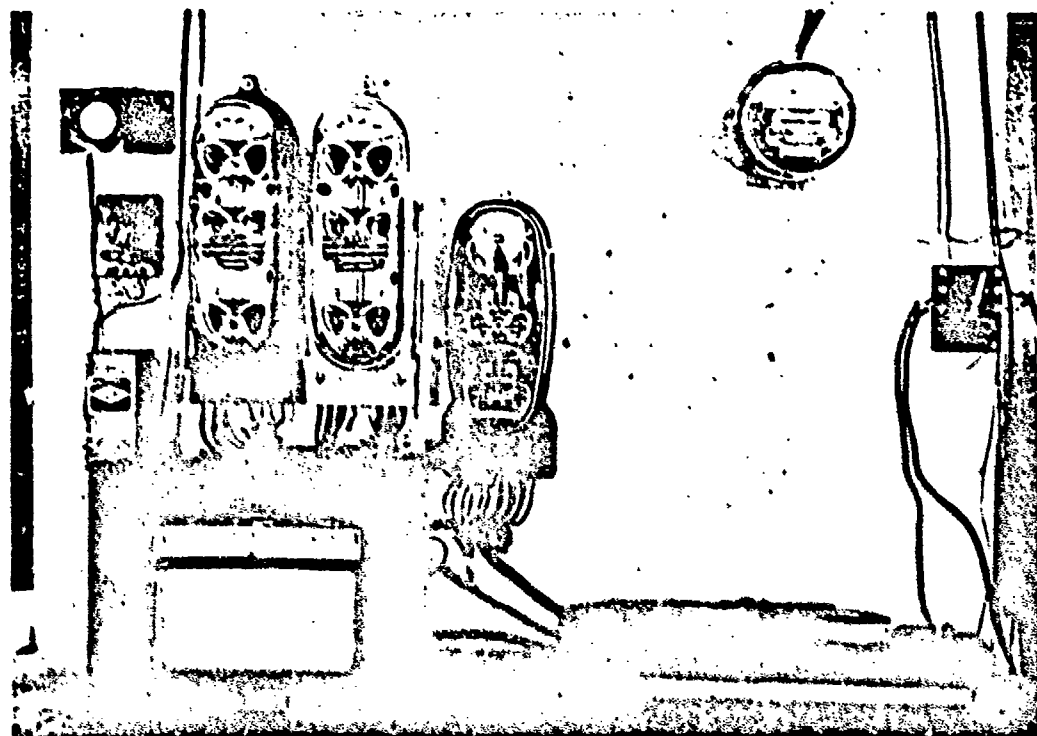
4. DIRECT VELOCITY MEASUREMENTS (ANEMOMETER)

The use of a hot wire anemometer for measuring air velocity at the inlet and outlet of the test space was also used as a method of determining air change rate.

The anemometer can be used to traverse the inlet and outlet opening and from the average velocities air change rates can be computed. However, there are several disadvantages to be found in its use. These are as follows:

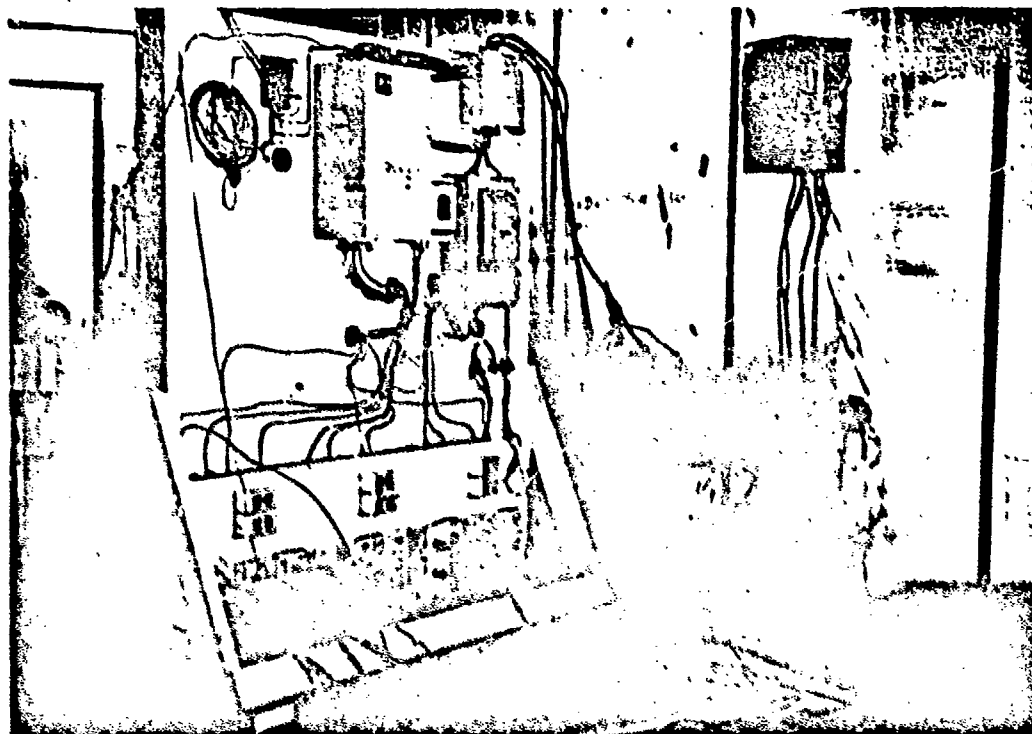
- a. The anemometer is seldom accurate over the range of velocities likely to be found in this type of study.
- b. Any cross flow at the inlet and outlet will not be detected.
Flow must be unidirectional across both openings.
- c. The results will depend largely on the ability of the research personnel in estimating the most accurate average for air velocities through the inlet and outlet.

All four methods of measuring air change rates which have just been discussed were utilized in this research project. Metering for the instrumentation and equipment was generally located on a master control panel board. Front and rear views of the control panel board are illustrated (Figures 13 and 14).



CONTROL PANEL BOARD (FRONT)

Figure 13



CONTROL PANEL BOARD (REAR)

Figure 14

CHAPTER 3

TEST BUILDING NO. 1

DESCRIPTION OF BUILDING AND TEST SPACE

For the first series of tests, an 8 story concrete and masonry dormitory (Figure 15) was selected because the building had natural "stacks" which would best utilize the variation of air density as the driving force for air movement. The air could rise through one stair tower, cross through the building near to top, move down the other stair tower, and return to the test space. Metal windows fit well and permitted an average amount of infiltration for this class of construction. A basement space, containing open wood racks (Figure 16) for trunk storage was selected for the test space. The approximate dimensions of this space are 58 x 17 feet with a ceiling height of 10 feet. The area is approximately 1000 square feet and the volume very close to 10,000 cubic feet. The total volume of the dormitory is 520,000 cubic feet.

The basement area (Figure 17) is completely below grade. The ground floor contains lobby, lounge and office space. Upper floors contain typical dormitory rooms (Figure 18) along the outside with a corridor running along both sides of an interior service core. The building was continually occupied and, therefore, all mechanical ventilation systems remained in operation.

In the test space the wood racks are built up to the ten foot high ceiling throughout. The empty racks were relocated to make space for the test equipment. Temporary partitions were constructed as shown (Figure 21). Inlet and outlet doors (Figures 19 and 20) had 1 x 2 inch mesh screen over them, providing open areas of 15.2 and 14.5 sq. ft. respectively, including the periphery door cracks. Fire doors provided entry into the stair towers. For the initial tests, all doors except the ones giving entry to the stair towers at the bottom and at the top were closed. Fire doors at those locations were opened as needed for the test being conducted. Locations of instruments and equipment are shown on a plan of the test space (Figure 21). Longitudinal and transverse sections show relative location of test space within the building (Figures 22 and 23). Doors labeled C, D, E and F (Figure 17) were closed so that a minimum of unmeasured circulating air was drawn from the elevator shaft and tunnel.

This building has many mechanical ventilating devices which influence the effective air reservoir. These include toilet exhaust systems, laundry driers, and unit ventilators at each floor level. The pumping action of the elevators also affects air circulation. Since the building was continuously occupied, it was not possible to close down any of the mechanical systems. At first glance, the presence of the operating mechanical systems might appear to nullify the test results. However, it is entirely conceivable that in a real emergency electric power could be available, and equipment which depends on that power could continue to operate. Therefore, this set of circumstances must certainly be considered as one possible situation.

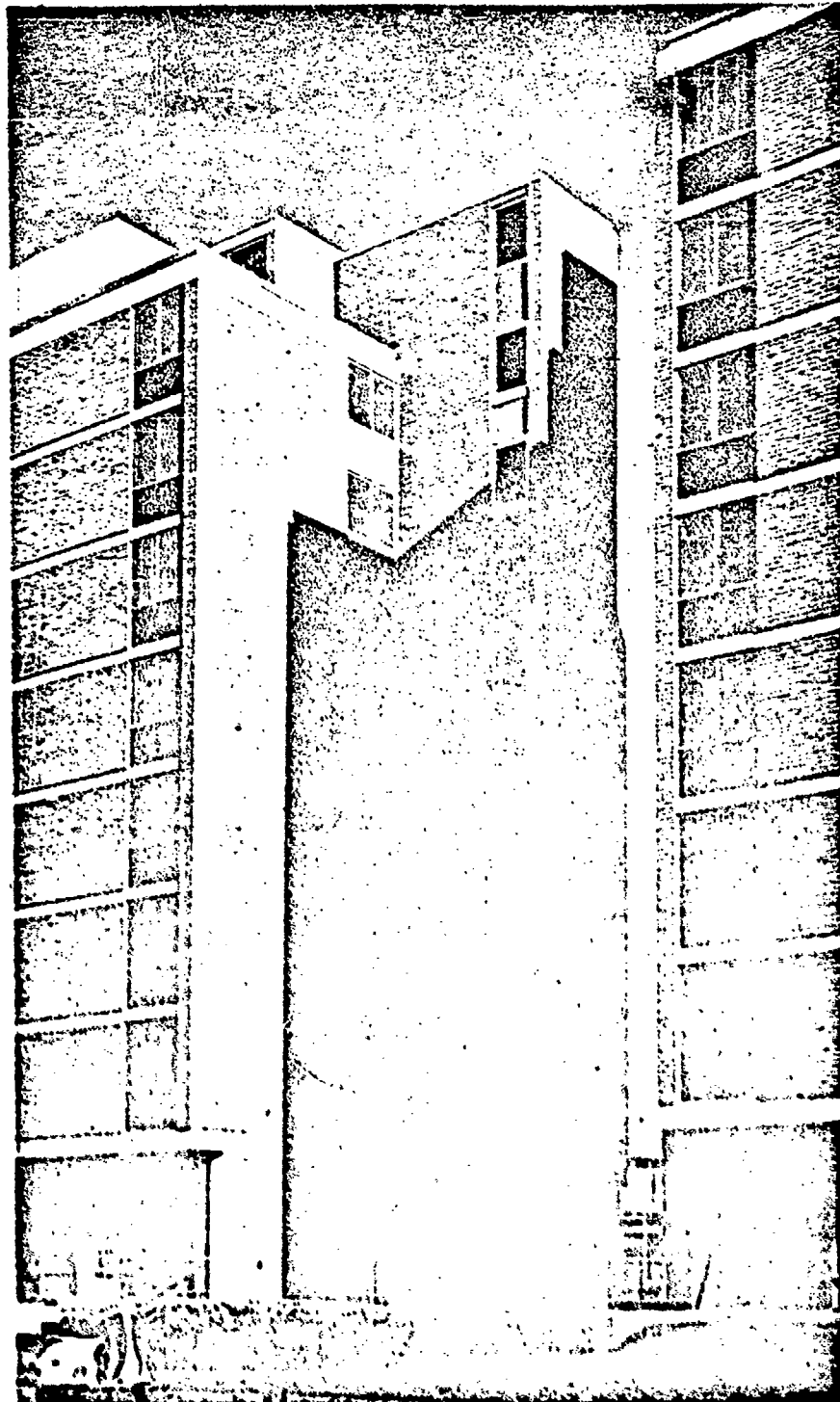
GENERAL PROCEDURE

The tests conducted in this building served three purposes: first, they provided data for the modification and improvement of test procedures and equipment; second, they uncovered problems in testing that could be expected in all the following buildings; and third, they gave a "feel" for the problem to be studied.

Most of the time spent in this occupied dormitory building was used to modify or correct the test equipment or test procedures. This involved the calibration of the power meters, repair of the recording potentiometers and perfection of a humidity input measurement system. All systems were performing properly at the same time during only a few days of this entire test period.

The obstacles encountered in testing in any large building are greatly multiplied when the building must function in a normal manner. Some of these obstacles were: (1) the windows were opened at random throughout the building, (2) the mechanical ventilation system ran continuously, and (3) the elevators and doors were used at frequent intervals. Therefore, it was decided that all future test work, insofar as possible, would be conducted in buildings that were unoccupied during the periods of observation.

The third and perhaps the most important purpose of this first series of tests was to obtain a "feel" for the problem. At first, the latent heat of the simulated occupants was supplied in only a token amount and the air change



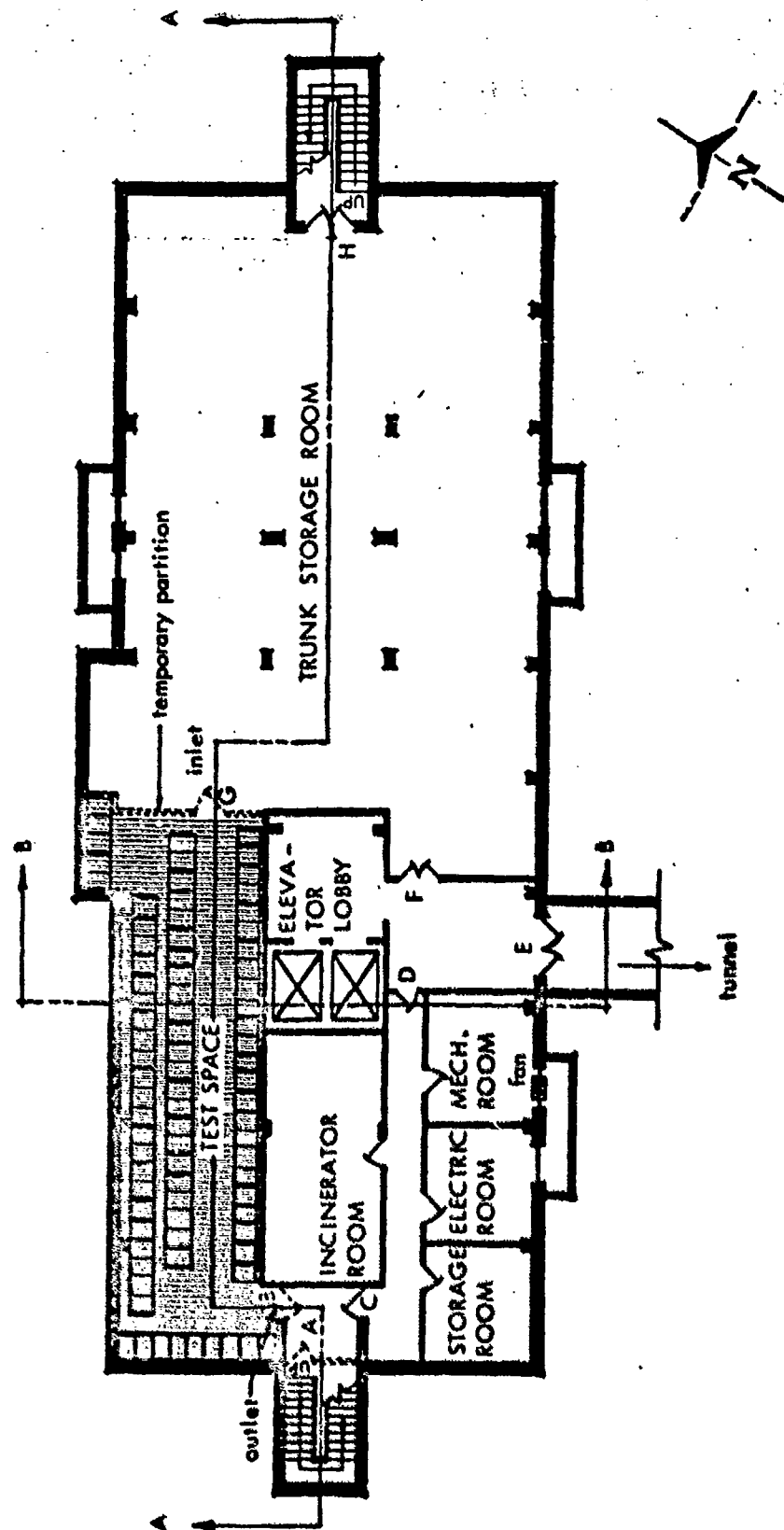
EXTERIOR VIEW — BUILDING NO. 1 (AT LEFT)

Figure 15



INTERIOR VIEW OF TEST SPACE

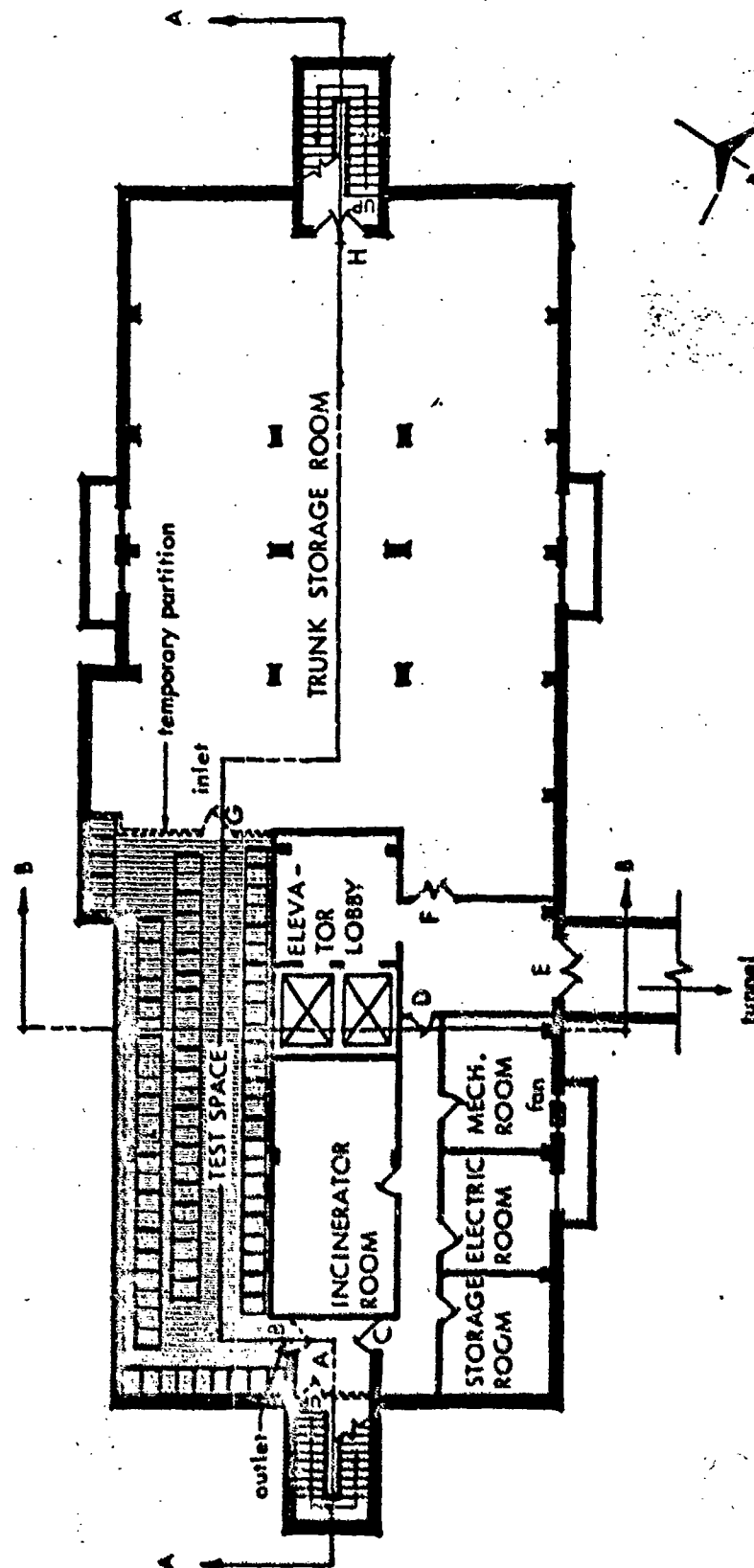
Figure 16



BASEMENT PLAN SHOWING TEST SPACE - BUILDING NO. 1

Scale: 1/16" = 1'-0"

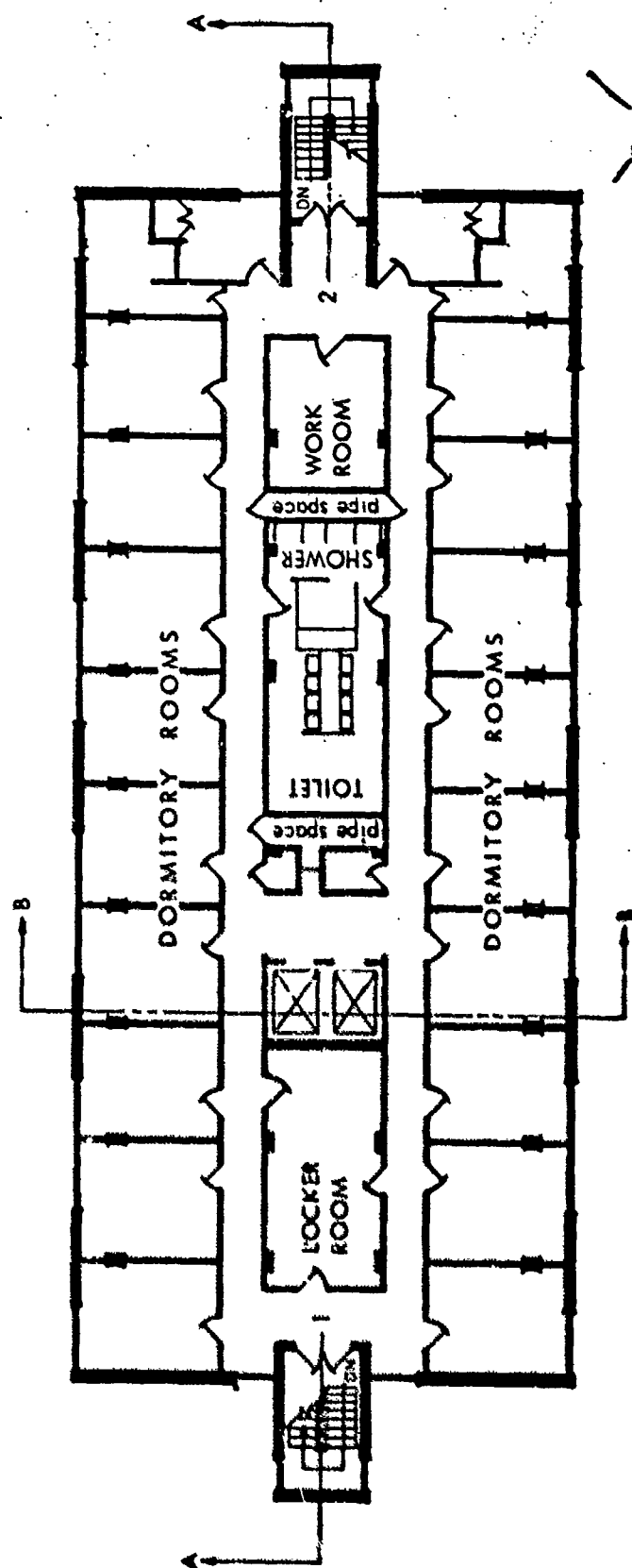
Figure 17



BASEMENT PLAN SHOWING TEST SPACE - BUILDING NO. 1

Scale: 1/16" = 1'-0"

Figure 17



NOTE: Location of cutting plane A-A varies between points 1 and 2 from basement to penthouse in order to portray the most essential items.

TYPICAL DORMITORY FLOOR PLAN - BUILDING NO. 1

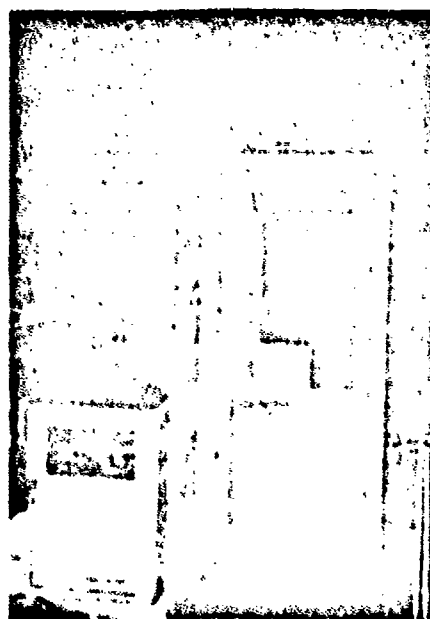
Scale: 1/16" = 1' - 0"

Figure 18



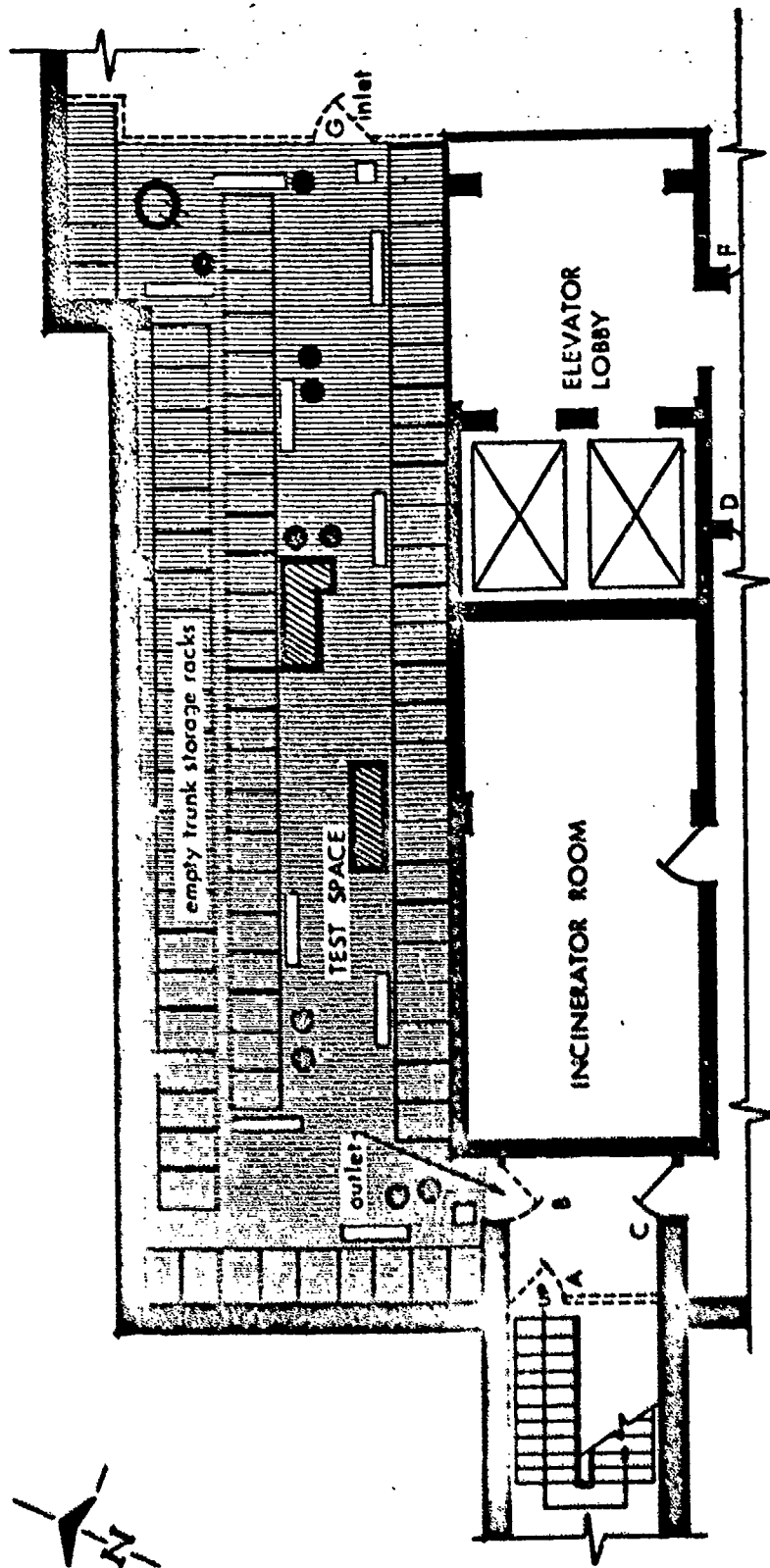
INLET DOOR IN TEST SPACE

Figure 19



OUTLET DOOR IN TEST SPACE

Figure 20



LEGEND:

- ===== temporary partitions
- tracer sensing device
- lamp bank
- humidifier barrel
- automatic psychrometer
- ▨ control panel stations

TEST SPACE PLAN - BUILDING NO. 1

Scale: 1/8" = 1'-0"

Figure 21

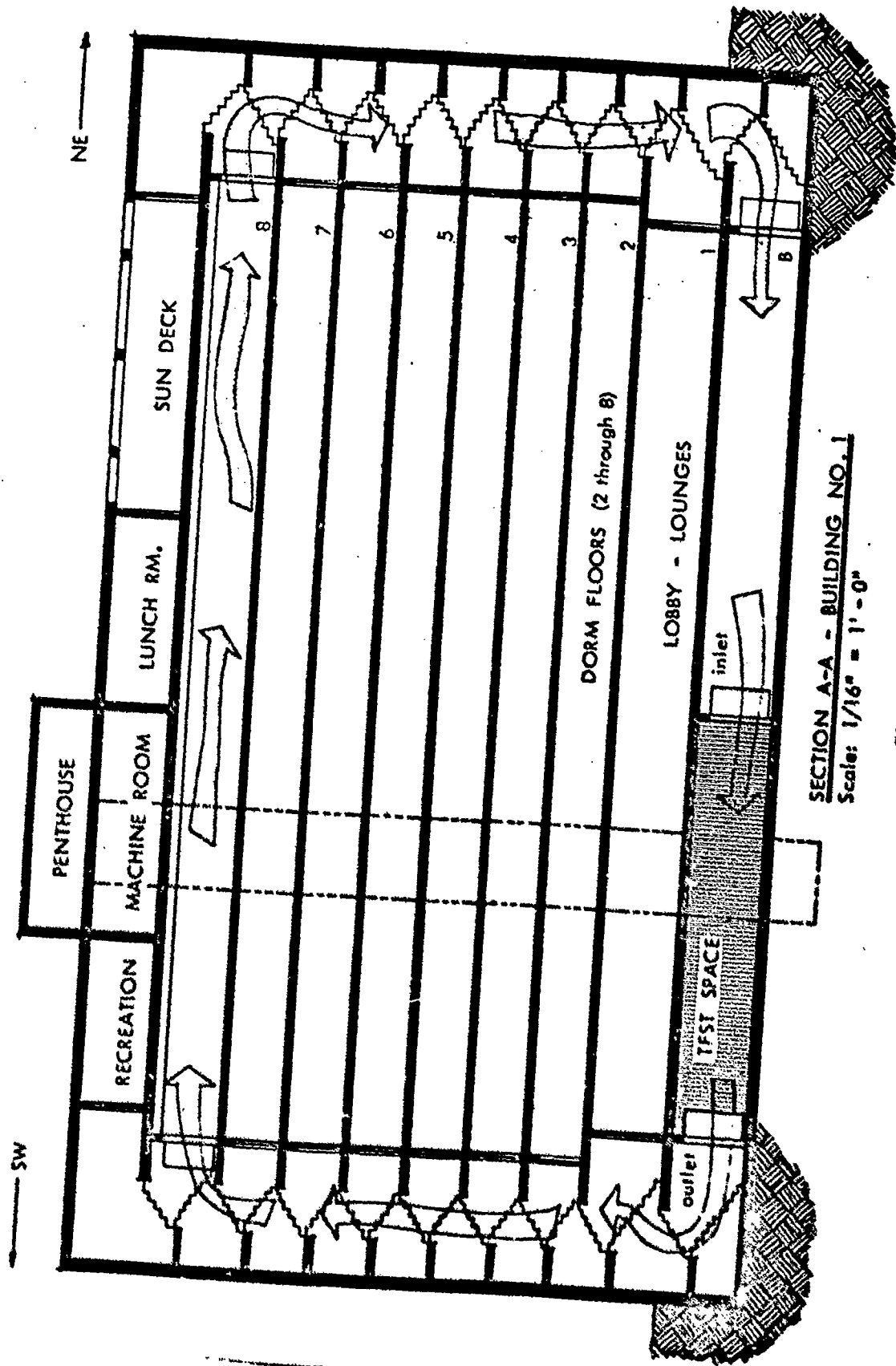
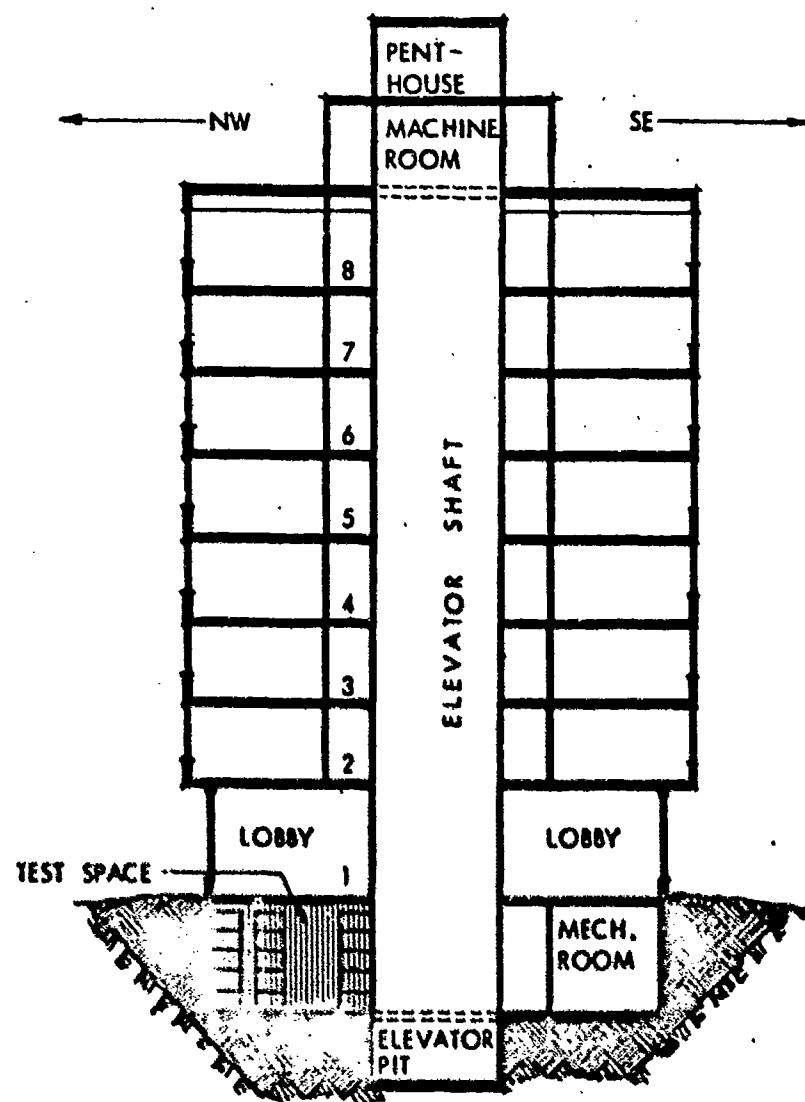


Figure 22



SECTION 8-8 - BUILDING NO. 1

Scale: $1/16" = 1' - 0"$

Figure 23

rate in the space was measured with the Portable Infiltration Meter using helium as the tracer gas. The instrument worked well with low air flows and low humidities, provided the temperatures in the test space did not fluctuate. However, upon introduction of higher humidities, the operation of the Portable Infiltration Meter became unreliable.

Four tests were conducted in this building. During the first three tests, guards were employed to keep the students from using the ground floor exits from the stair towers. This helped to stabilize conditions in the test space more rapidly. The first three test situations were conducted with low humidity input.

TEST RESULTS

When air flows or is infiltrated into a test space at a steady rate, the tracer gas concentration decreases along a logarithmic curve as indicated by Equation (2). When plotted on semi-logarithmic paper, the decay curve must be a straight line. When the air flows through the space in a positive direction, sensing devices stationed at different locations in the test space indicate different air change rates.

Near the Inlet (Figure 21) a higher air change rate was indicated than near the outlet. Since the air moving through the space carries some helium with it, decay would not be as rapid near the outlet. Decay curves A and B (Figure 9) were obtained during a typical test. Curve A is the plot of air change rate obtained from a sensing device near the inlet while curve B is

that from a sensing device near the outlet. The indicated difference in air change rate is caused by the movement of helium-laden air from the inlet to the outlet, the apparent rate of change near the outlet being smaller. The application of Equation (2) results in an air change rate near the inlet greater than that near the outlet. At all times during the simulated occupancy of the test space, the direction of air movement was from north-east to southwest, or from G to B (Figure 21) as anticipated on the basis of relative location of test space and stair towers, and exposure of the southwest stair tower to solar radiation.

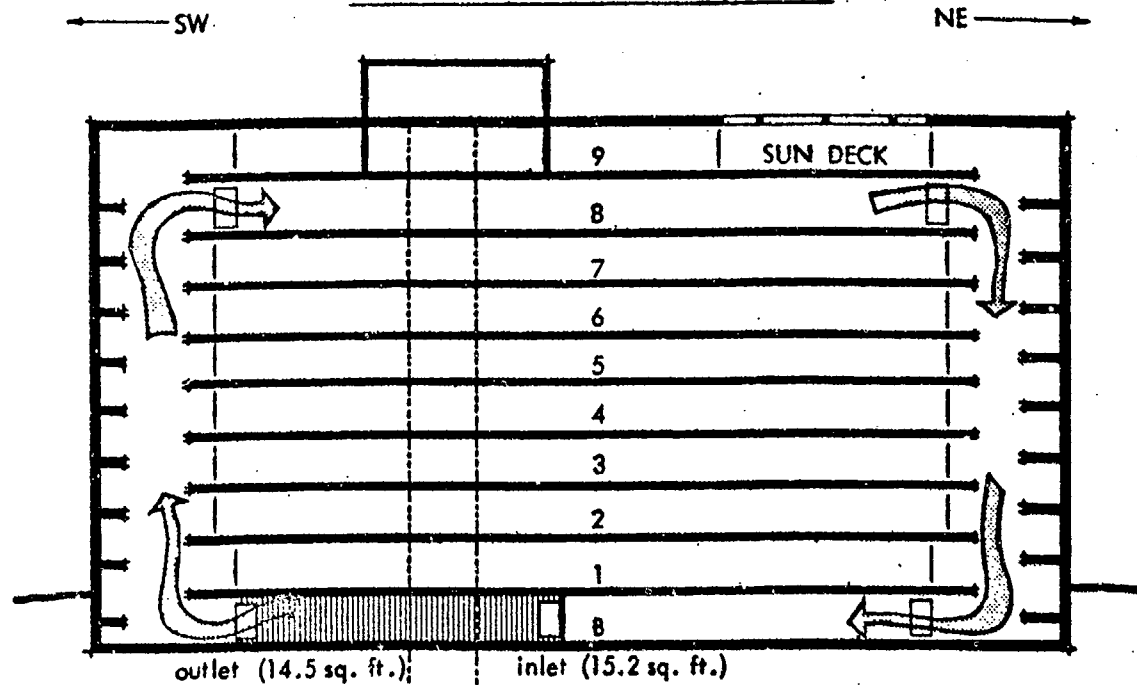
Test #1 (Figure 24) required that the stair tower doors on the 7th or top occupied floor of the building and the inlet and outlet doors of the basement test space be open. All other doors in the basement were to be closed but not sealed. The air change rate developed was between 3 and 5 air changes per hour with the space temperature stabilized at 82 F. Occupancy was simulated on the basis of 10 sq. ft. of floor area per person. These conditions appear to provide good shelter occupancy, but it should be remembered that the mechanical ventilation system was functioning at all times. Also, fresh air was admitted through doors used by students entering and leaving the building and through open windows in dormitory rooms.

BUILDING NO. 1

TEST NO. 1

4/5/62 (0000) - 4/6/62 (1400)

100 OCCUPANTS - 10 SQ. FT./PERSON



OUTSIDE CONDITIONS

air temperature	48 - 56F
relative humidity	48 - 96%
wind	SW 7 mph
comments	cloudy

EFFECTIVE TEMPERATURE (based on full moisture load)

ave. outlet (3' ht.)	★
ave. outlet (5' ht.)	★

DRY BULB TEMPERATURE

ave. inlet (entire door)	71.0F
ave. outlet (entire door)	83.0F
ave. room (5' ht.)	82.0F

RATE OF AIR FLOW

helium method	
cfm/person	5 to 8
air changes/hour	3 to 5

WET BULB TEMPERATURE (based on full moisture load)

3' ht. ave. inlet	★
ave. outlet	★
5' ht. ave. inlet	★
ave. outlet	★

COMMENTS

Approx. 2 lb/hr moisture input (token load).
Humidity input measurement inaccurate.
• Wet bulb and effective temperatures too inaccurate to record.

Figure 24

Test #2 (Figure 25) was run with the test space inlet and outlet open but all doors above basement level closed. However, occupants of the building continued to use the upper floor doors in their normal activities. The only incoming air to the test space was supplied by leakage through the cracks around the stair tower doors. As might be expected, the air change rate dropped to between 3 and 4 changes per hour with an average temperature in the test space of 83 F.

Test #3 (Figure 26) was used to determine the influence of tunnel and other extraneous infiltration, since there were underground tunnels connecting the buildings of the dormitory group. All doors above basement level were closed as was the northeast stair tower door at basement level. Another door in the basement connecting the tunnel with a trunk room adjacent to the test space, Door F (Figure 17), had a bottom louvered panel. This door was closed but the two louvers, gross 13 x 17 inches each, remained open at all times. The air change rate under this condition dropped to between 2 and 3 air changes per hour.

Test #4 (Figure 27) was conducted to determine if a horizontal circulation loop could be set up in the basement while the mechanical ventilation continued to operate in the basement and while air flowed through the tunnel. The horizontal circulation loop can best be described with reference to the basement plan (Figure 17). Air flow occurred on a counter clockwise manner from the test space through doors B, C, D, F and back to the test space through inlet door G. Access to stair towers at basement

level was closed off and all other doors in the basement were closed except those four which were necessary to form the circulation loop. A rate of approximately 3 air changes per hour was obtained. It was possible, however, that most of the indicated change was caused by recirculation of test space air with only a small percentage of fresh infiltration air included. Further tests are needed to clarify this situation.

For this test a realistic ratio of latent to sensible heat was supplied to the test space. This was the only test to date in which that ratio was held closely, and with due regard to an actual situation. Previous tests used only token moisture loads to prevent damage to the building on upper floors. Under this condition of high humidity, the air change rate could not be determined with the Portable Infiltration Meter. Therefore, air change rate was approximated by using the known amount of evaporated water and the increase of humidity in the test space.

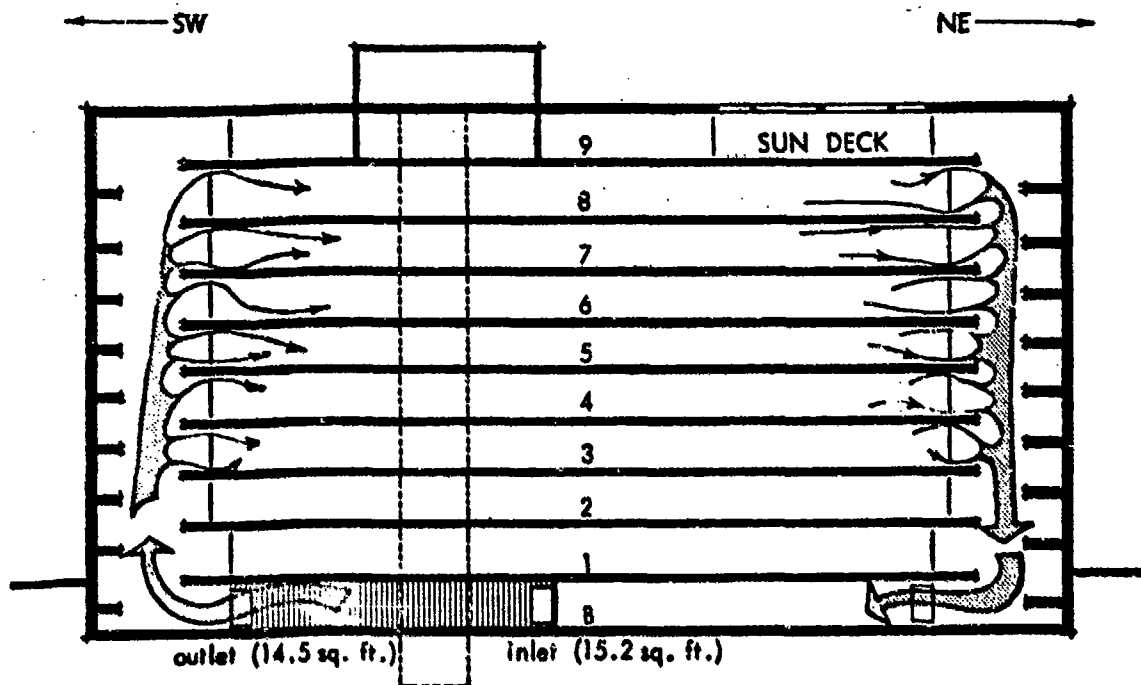
A summary of the pertinent data collected during the tests in Building No. 1 is presented in Table 4. The various air flow circuit configurations are also presented (Figure 28). The problems encountered in attempting to establish equilibrium through controlling the movements of the building occupants were considerable. Therefore, it was decided to move next into a building where conditions could be controlled with relative ease.

BUILDING NO. 1

TEST NO. 2

4/6/62 (1400) - 4/6/62 (2300)

100 OCCUPANTS - 10 SQ. FT./PERSON



OUTSIDE CONDITIONS

air temperature 49 - 52F
relative humidity 90 - 96%
wind SSW 2-4 mph
comments rain

EFFECTIVE TEMPERATURE (based on full moisture load)

ave. outlet (3' ht.) *
ave. outlet (5' ht.) *

DRY BULB TEMPERATURE

ave. inlet (entire door) 76.0F
ave. outlet (entire door) 82.0F
ave. room (5' ht.) 83.0F

RATE OF AIR FLOW

helium method
cfm/person 6 to 8
air changes/hour 4 to 5

WET BULB TEMPERATURE (based on full moisture load)

3' ht. ave. inlet *
ave. outlet *
5' ht. ave. inlet *
ave. outlet *

COMMENTS

- Approx. 2 lb/hr moisture input (token load)
- Humidity input measurement inaccurate.
- Wet bulb and effective temperatures too inaccurate to record.

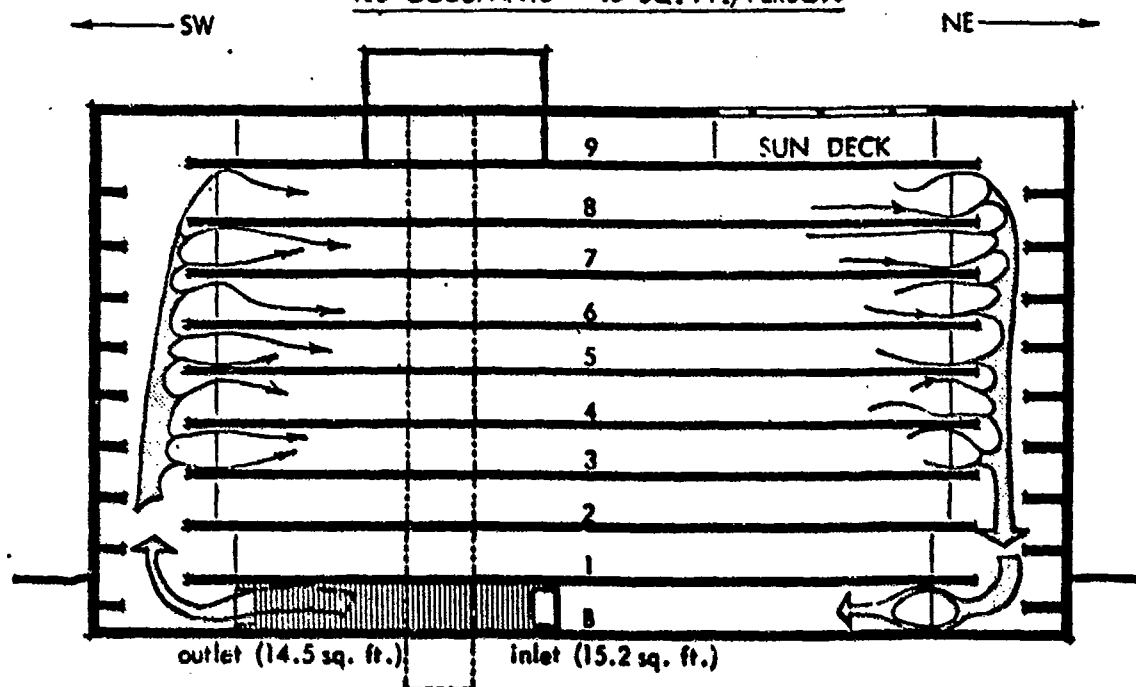
Figure 25

BUILDING NO. 1

TEST NO. 3

4/9/62 (0800) - 4/9/62 (2000)

100 OCCUPANTS - 10 SQ. FT./PERSON



OUTSIDE CONDITIONS

air temperature 45 - 50F
 relative humidity 49 - 96%
 wind SSW 2-5 mph
 comments cloudy to rain

EFFECTIVE TEMPERATURE (based on full moisture load)

ave. outlet (3' ht.) •
 ave. outlet (5' ht.) •

DRY BULB TEMPERATURE

ave. inlet (entire door) 73.0F
 ave. outlet (entire door) 83.0F
 ave. room (5' ht.) 82.0F

RATE OF AIR FLOW

helium method
 cfm/person 3 to 4
 air changes/hour 2 to 2.5

WET BULB TEMPERATURE (based on full moisture load)

3' ht. ave. inlet •
 ave. outlet •
 5' ht. ave. inlet •
 ave. outlet •

COMMENTS

- Approx. 2 lb/hr moisture input (token load)
- Humidity input measurement inaccurate.
- Wet bulb and effective temperatures too inaccurate to record.

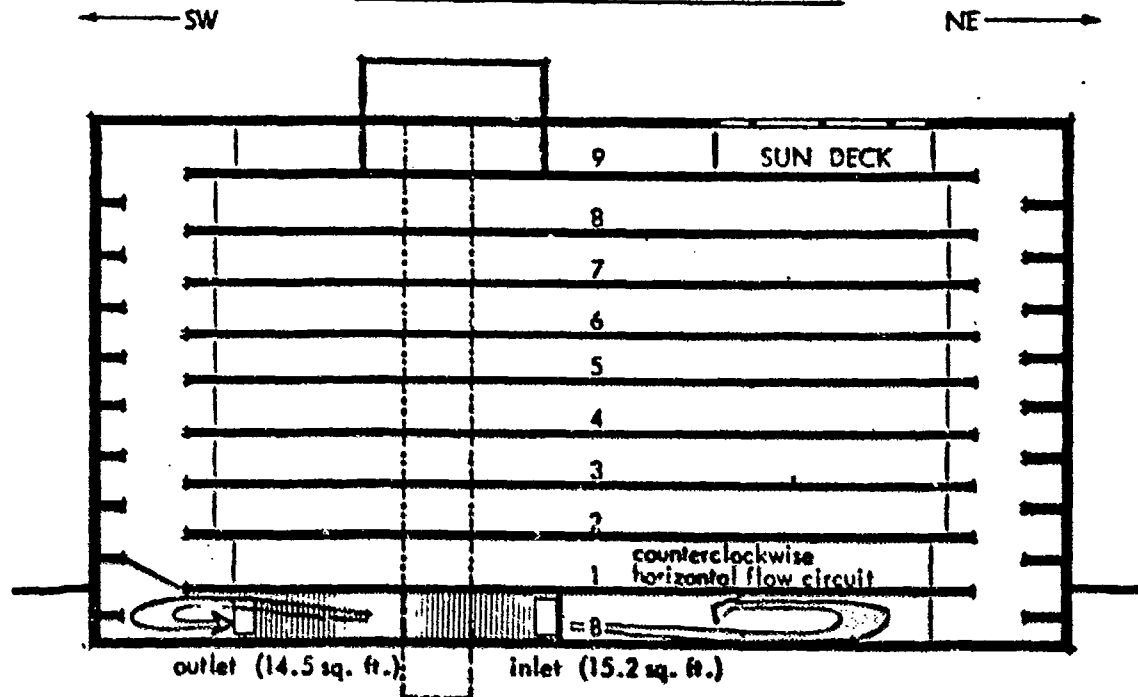
Figure 26

BUILDING NO. 1

TEST NO. 4

5/4/62 (0900) - 5/6/62 (0800)

100 OCCUPANTS - 10 SQ. FT./PERSON



OUTSIDE CONDITIONS

air temperature 55 - 82F
 relative humidity 13 - 40%
 wind W 8-15 mph
 comments clear, sunny

EFFECTIVE TEMPERATURE (based on full moisture load)

ave. outlet (3' ht.) 80.0F

DRY BULB TEMPERATURE

ave. inlet (entire door) 70.0F
 ave. outlet (entire door) 84.0F
 ave. room (5' ht.) 83.0F

RATE OF AIR FLOW

water vapor method
 cfm/person 4.0 to 5.5
 air changes/hour 2.5 to 3.5

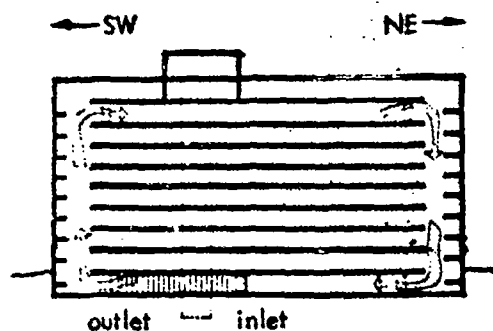
WET BULB TEMPERATURE (based on full moisture load)

3' ht. ave. inlet 62.5F
 ave. outlet 77.5F

COMMENTS

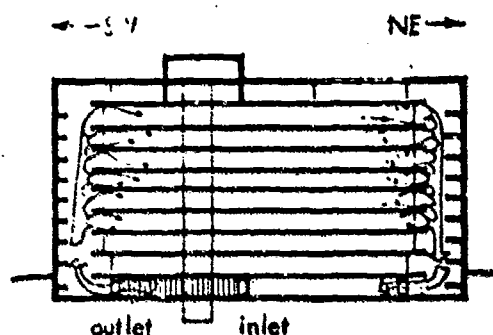
High moisture input.
 No method used to determine fresh
 air infiltrated to circulating air.

Figure 27



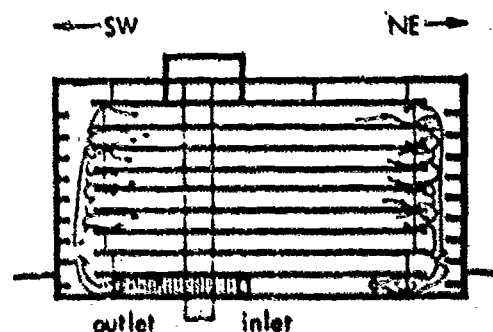
TEST NO. 1

Stair tower doors open on eighth story.
Other doors and elevators in frequent use.
Windows open at random.
Mechanical ventilation system operating.
Vol. ratio — test space to circulation space = 0.15.
Inlet opening 15.2 sq. ft.
Outlet opening 14.5 sq. ft.



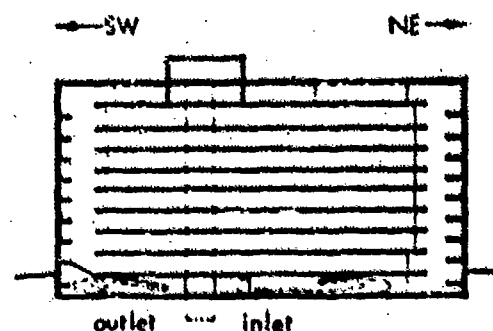
TEST NO. 2

Doors and elevators in frequent use.
Windows open at random.
Mechanical ventilation system operating.
Vol. ratio — test space to circulation space = 0.20.
Inlet opening 15.2 sq. ft.
Outlet opening 14.5 sq. ft.



TEST NO. 3

NE stair tower door closed at basement level.
Doors and elevators in frequent use.
Windows open at random.
Mechanical ventilation system operating.
Vol. ratio — test space to circulation space = 0.25.
Inlet opening 15.2 sq. ft.
Outlet opening 14.5 sq. ft.



TEST NO. 4

Access to stair towers at basement level closed.
Horizontal circulation loop formed by opening
of other basement doors. (doors C, D, E, and F
in Figure 17)
Mechanical ventilation system operating.
Vol. ratio — test space to circulation space = 0.30.
Inlet opening 15.2 sq. ft.
Outlet opening 14.5 sq. ft.

COMPARISON OF AIR FLOW CIRCUIT CONFIGURATIONS — BUILDING NO. 1

Figure 28

Table 4

TEST SUMMARY BUILDING NO. 1

TEST NO.	1	2	3	4
Duration of test	38 hrs.	9 hrs.	12 hrs.	47 hrs.
Simulated occupancy	100	100	100	100
Floor area per person	10 sq. ft.	10 sq. ft.	10 sq. ft.	10 sq. ft.
Outside conditions				
air temperature	48-56F	49-52F	45-50F	55-82F
relative humidity	48-96%	90-96%	49-96%	13-40%
wind direction	SW	SSW	SSW	W
wind speed	7 mph	2-4 mph	2-5 mph	8-15 mph
comments	cloudy	rain	cloudy to rain	clear, sunny
Dry bulb temperature				
ave. inlet	71.0F	76.0F	73.0F	70.0F
ave. outlet	83.0F	82.0F	83.0F	84.0F
ave. room	82.0F	83.0F	82.0F	83.0F
Wet bulb temperature				
ave. inlet (3')	$\frac{\cdot}{\cdot}$	$\frac{\cdot}{\cdot}$	$\frac{\cdot}{\cdot}$	62.5F
ave. outlet (3')	$\frac{\cdot}{\cdot}$	$\frac{\cdot}{\cdot}$	$\frac{\cdot}{\cdot}$	77.5F
ave. inlet (5')	$\frac{\cdot}{\cdot}$	$\frac{\cdot}{\cdot}$	$\frac{\cdot}{\cdot}$	$\frac{+}{+}$
ave. outlet (5')	$\frac{\cdot}{\cdot}$	$\frac{\cdot}{\cdot}$	$\frac{\cdot}{\cdot}$	$\frac{+}{+}$
Effective temperature				
ave. inlet (3')	$\frac{\cdot}{\cdot}$	$\frac{\cdot}{\cdot}$	$\frac{\cdot}{\cdot}$	80.0F
ave. outlet (5')	$\frac{\cdot}{\cdot}$	$\frac{\cdot}{\cdot}$	$\frac{\cdot}{\cdot}$	$\frac{+}{+}$
Air flow				
cfm/person	5 to 8	6 to 8	3 to 4	4.0 to 5.5
air change/hour	3 to 5	4 to 5	2 to 2.5	2.5 to 3.5
Comments	Taken moisture load. *Measurement unreliable.	Taken moisture load. *Measurement unreliable.	Taken moisture load. *Measurement unreliable.	High moisture load. +Not recorded.
Portable Infiltration Meter used for determining air change rates with helium tracer gas except in Test #4 where the water vapor method was applied.				

CHAPTER 4

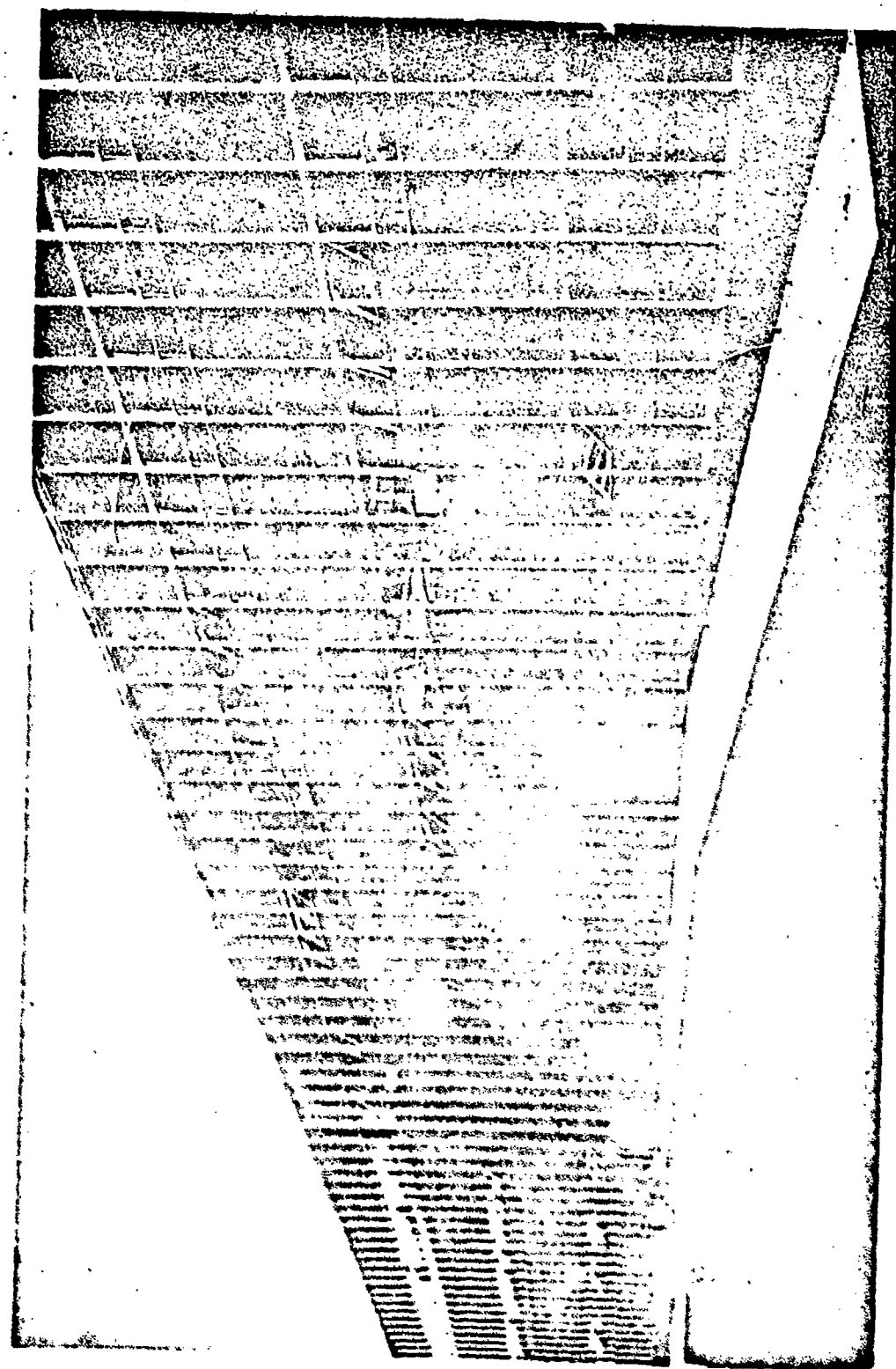
TEST BUILDING NO. 2

DESCRIPTION OF BUILDING AND TEST SPACE

This is essentially a three story classroom-laboratory-shop building with full basement and partial sub-basement. Construction is concrete frame and floor slabs with metal curtain wall exterior. The metal panels fit tightly so that leakage is a minimum. The ends of the building and the front wall of the basement level are faced with local stone. Metal windows fit tightly and permit less than average infiltration. A photograph of the rear of the building is shown (Figure 29).

The test space, located in the sub-basement in the general position of the concrete ramp (Figure 29) has a net floor area of approximately 1,600 square feet and a volume of approximately 16,000 cubic feet. The ratio of test space volume to total circulation space volume is approximately 1 to 5. A large plywood surfaced wind tunnel, accounting for an additional 4,350 cubic feet was completely sealed off from the test space.

The test space itself was sealed off by taping, except for doors where air was expected to enter and exit the space. Air entered through a door opening of 20.4 sq. ft. and exited either through a screened door providing 14.5 sq. ft. of opening, or through a long horizontal slit in the upper portion of a partition wall with an opening area of 68.8 sq. ft. maximum, depending on the particular test involved.



EXTERIOR VIEW — BUILDING NO. 2

Figure 29

The space adjacent to the test space also had sealing tape applied to door cracks and to cracks around pipes so that outside air would not affect the air flow circuit. A floor plan of the test space (Figure 30) shows location of instruments and equipment, and the closed off wind tunnel.

The basement above the sub-basement test space (Figure 31) served as a circulation space and was completely sealed off from external disturbances except for one door and a grille in the floor. All pipe entrance cracks were sealed with tape. The only possible disturbance of any magnitude from outside the air flow circuit would have come from a row of seventeen hopper-type windows, each about 3 feet by 4 feet, located about eight feet above floor level. Those windows were always closed but were not sealed with tape.

Two interior walls in the circulation space are concrete block with occupied rooms adjoining. One exterior wall is solid concrete with a roofed space on the outer side protected from the weather but not heated. The other exterior wall containing the high windows is concrete block with stone facing.

Sections through the test space and circulation space are shown (Figures 32 and 33). Stairway A connects basement circulation space and sub-basement test space only, but stairway B and the elevator shaft extend from the sub-basement level to the top story of the building. General paths of air flow are indicated on these section drawings. An interior view of the test space is also shown (Figure 34).

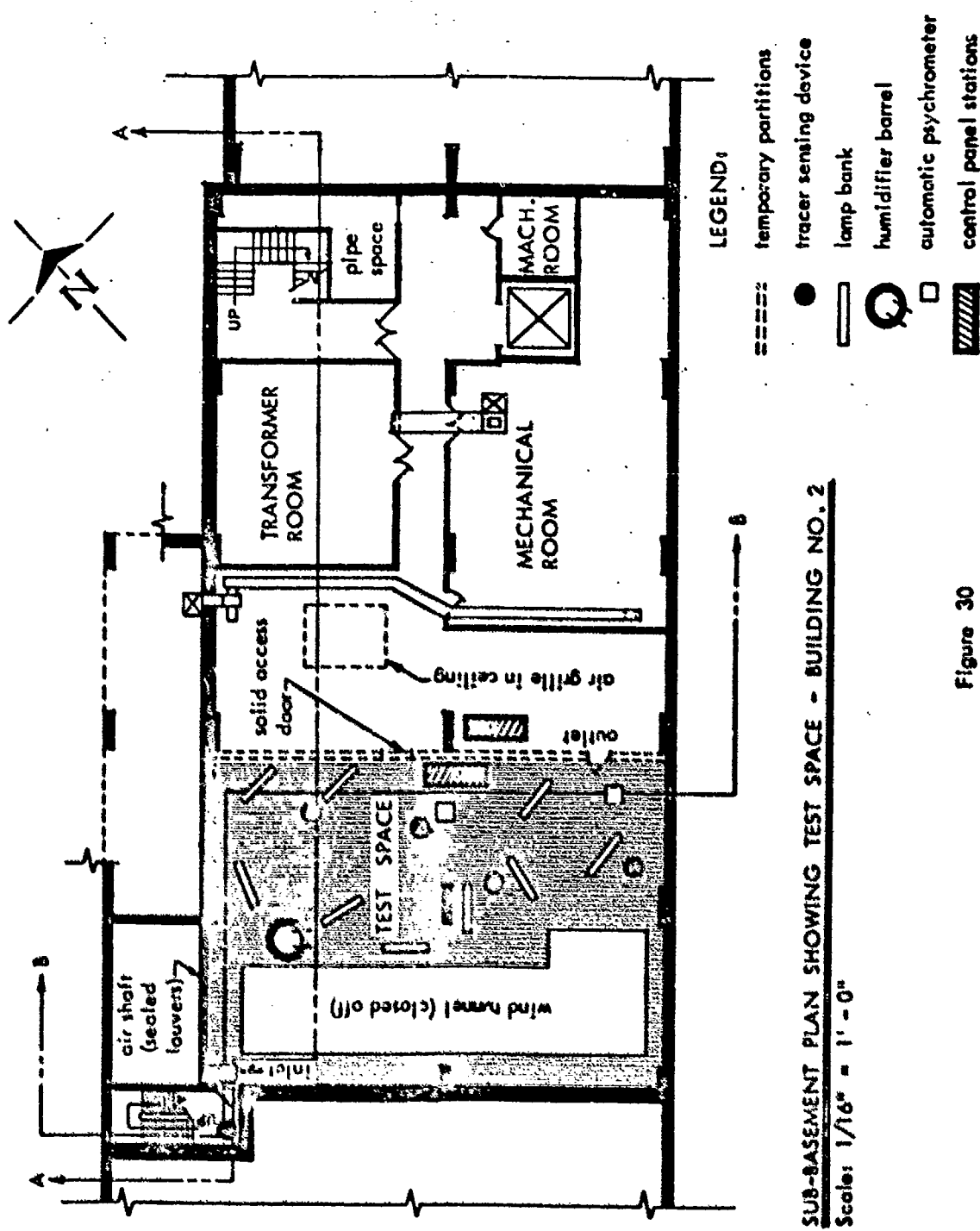
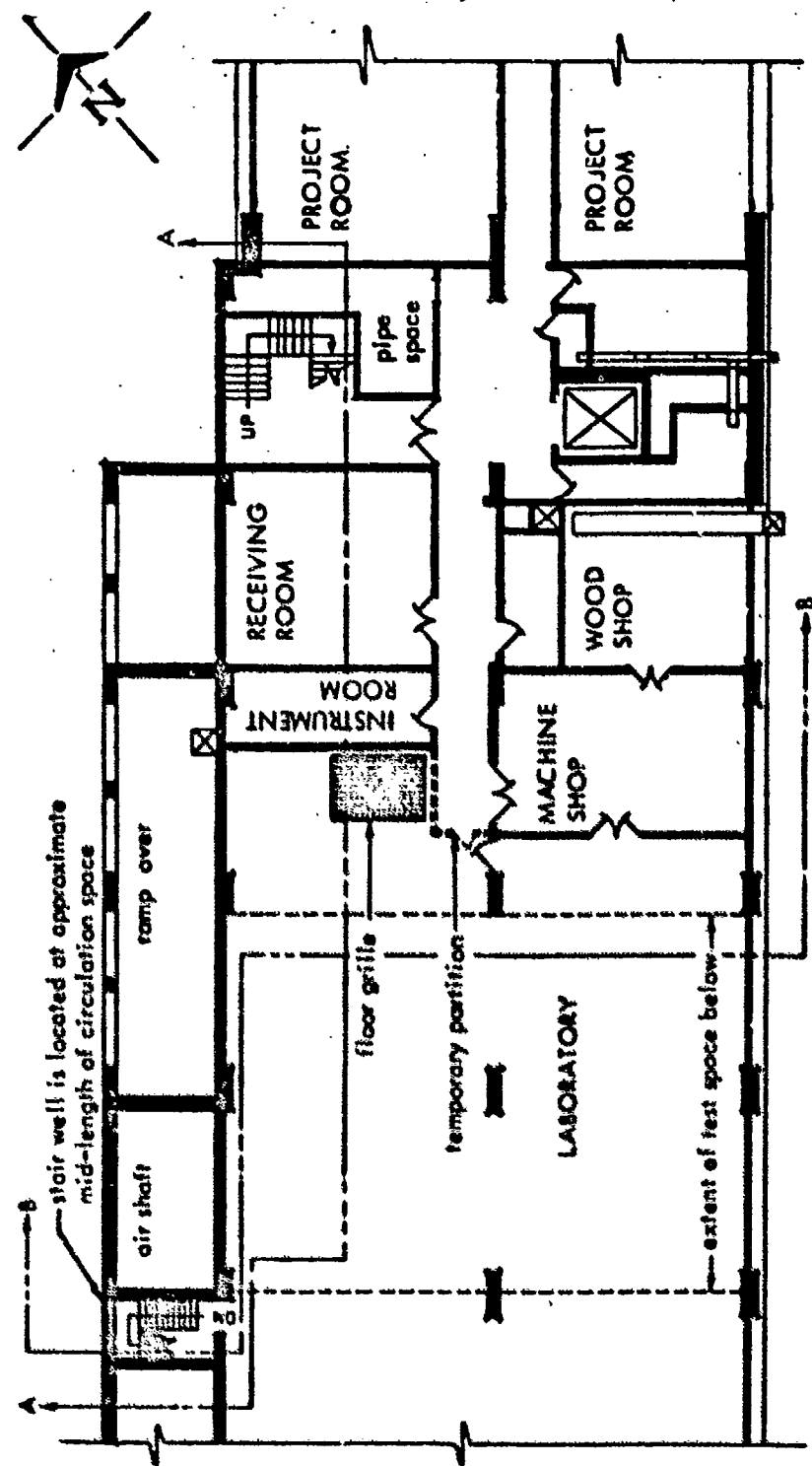
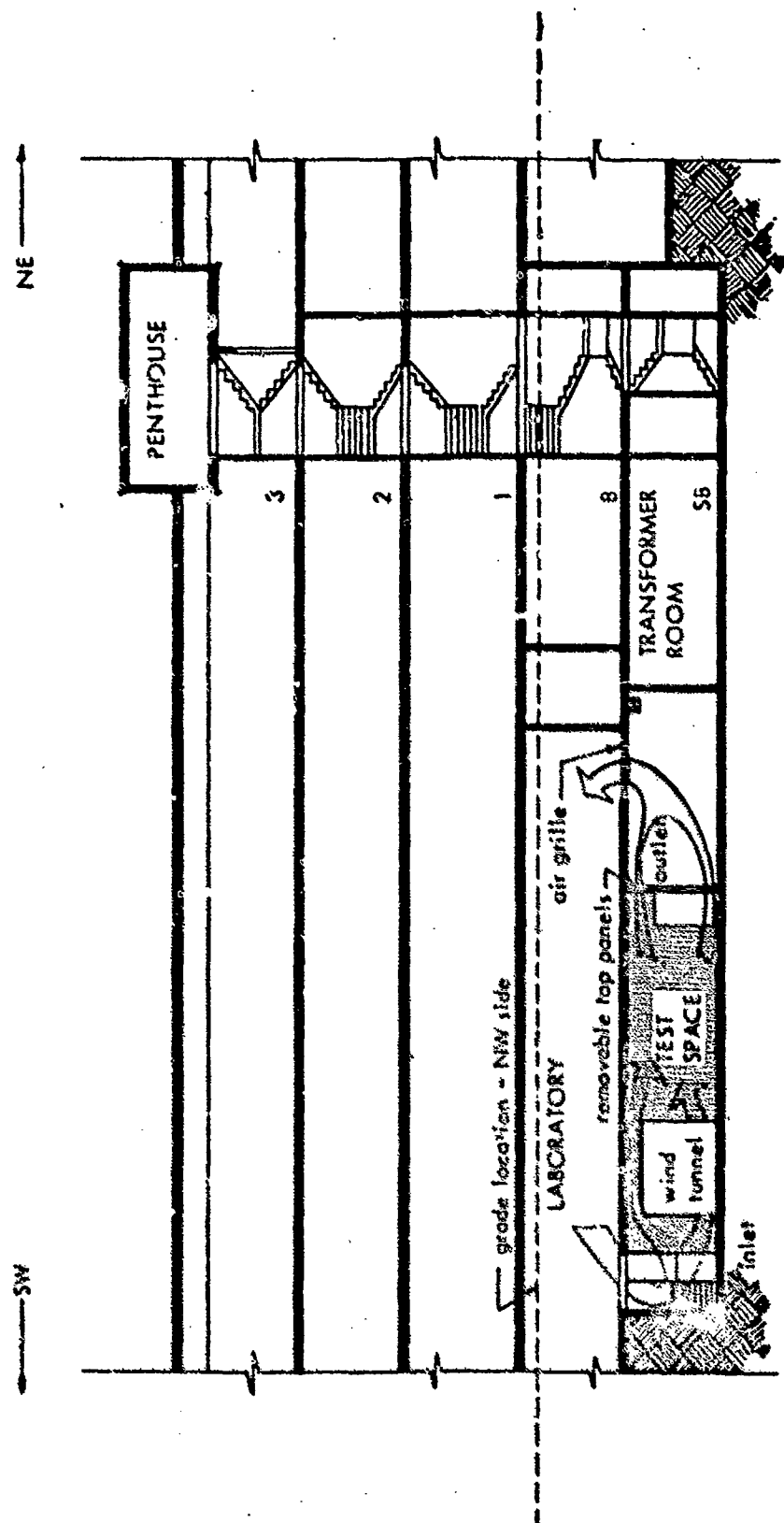


Figure 30



BASEMENT PLAN - BUILDING NO. 2
 Scale: 1/16" = 1'-0"

Figure 31

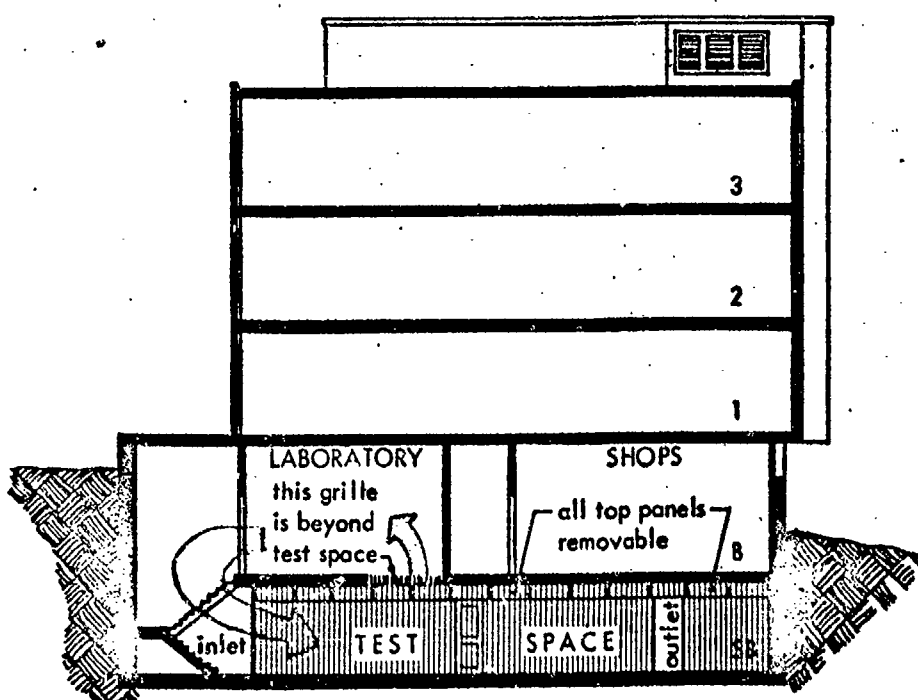


SECTION A-A - BUILDING NO. 2

Scale: 1/16" = 1' - 0"

← NW

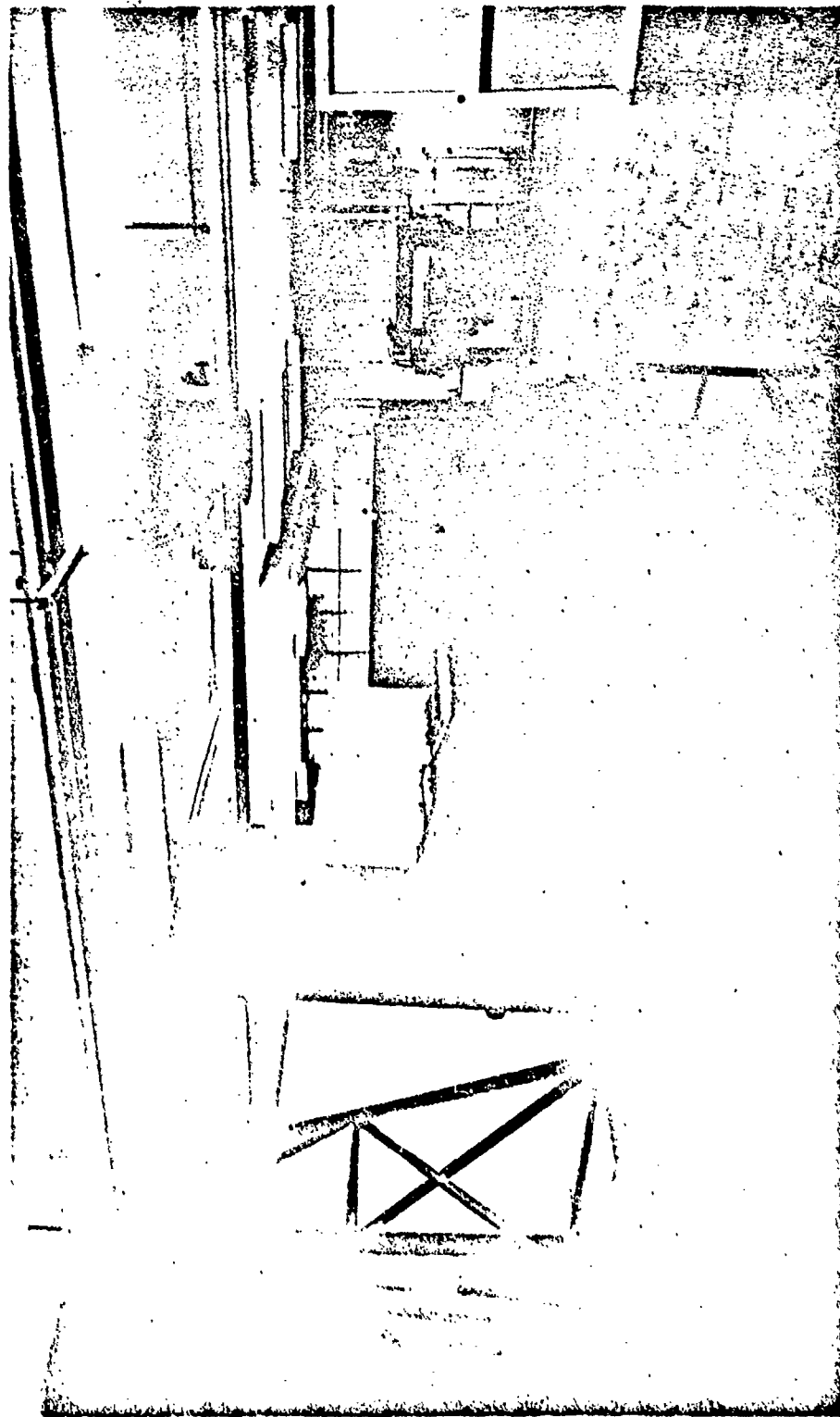
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SECTION B-B - BUILDING NO. 2

Scale: 1/16" = 1' - 0"

Figure 33



INTERIOR VIEW OF TEST SPACE

Figure 34

GENERAL PROCEDURE

The principle objective of the tests conducted in this building was to study the nature and magnitude of gravity air flow in a low building. For this reason, air flow paths were confined to the two stories consisting of basement and sub-basement. Air change rates were determined by the water vapor method, and with the Portable Infiltration Meter using helium as a tracer gas. However, malfunctioning of equipment under continuous use in high temperature and humidity conditions sometimes produced misleading data on the Portable Infiltration Meter Indicator.

In general, the following procedure, proposed as a result of testing in Building No. 1, was to be used in all succeeding tests in Building No. 2 and Building No. 3:

1. The terminal equilibrium air conditions are estimated. This estimate does not have to be extremely accurate since adjustments can be made later if the estimation proves to be incorrect. With an estimated dry bulb temperature and humidity the sensible heat load per occupant is selected from Table 1. The occupancy is determined at 1 person per 10 square feet of floor area. With these two figures known, the total sensible heat input can be computed.
2. Heat is supplied at the computed rate plus sufficient heat to evaporate 5 lbs. of water per hour. This is a token latent load to provide water vapor balance.

3. The actual temperatures are observed and the air change rate is obtained by use of the Portable Infiltration Meter utilizing a helium tracer, the water vapor balance, or any other suitable method.
4. From the known inlet air conditions and the sensible and latent heat loads of Table 1, the terminal or outlet temperature and humidity can be calculated.
5. The outlet effective temperature can be determined (Figure 7).
6. If the outlet effective temperature exceeds 85 F, a value arrived at in previous studies dealing with tolerable shelter limits (Reference 7), the air change rate will be judged to be insufficient to support the number of occupants assumed in Step 1 above.

Readings were made from the time heat and water vapor were introduced into the test space in order to approximate the actual conditions of sudden movement of people into a shelter with normal air conditions. However, the rapid increase in dry bulb temperature in this situation indicated very quickly the need to reduce the number of occupants simulated in this particular test space. This change in heat input was made a few hours prior to the first recorded series of tests.

The specific approach to the habitability of the test space was as follows:

1. Determine the usable floor area in the test space.
2. Use approximately 10 sq. ft. per person for occupancy.

3. Set sensible load for the given initial temperature of the test space according to normal heat dissipation level from Table 1.
4. Use a humidification rate of 5 lb./hr. total.
5. Observe air temperature rise in test space and cut back the sensible load accordingly.
6. If the calculated effective temperature at the outlet reached 85 F the test space was to be reduced in "occupancy."
7. With a greater sq. ft. area per person, repeat steps 3 to 6.
8. If the effective temperature is still too high increase the outlet area by removing panels along the top of the partition wall.

TEST RESULTS

Test #1 in Building No. 2 (Figure 35) was started at 1:00 pm on June 9, 1962 using 250 Btu/person per hour sensible head load and a token latent load of 5 lbs. moisture per hour. Approximately 150 occupants were being simulated which allowed about 10 sq. ft. per person. The screened door provided a 14.5 sq. ft. outlet opening. The dry bulb temperature in the test space was 75.6 F.

At 10:00 am on June 10, the sensible load was again reduced, this time to 150 Btu/person per hour because the space temperature had risen to 85.4 F. Although equilibrium had not yet been established, since the space temperature was still rising at the rate of 0.07 degrees F/hr., space conditions were then calculated. Average room temperature was above average outlet temperature, indicating that there was "trapped" air not mixing in

the air stream. Indications showed that, for 10 sq. ft. per person and the outlet area restricted to one open door, test space conditions were inadequate to hold to an effective temperature of 85 F. However, an air change rate on the order of 4.0 per hour was determined by the water vapor method.

In Test #2 (Figure 36) the air flow circuit remained unchanged. Occupancy was reduced to approximately 100 people or 15 sq. ft. per person. Air temperatures were still rising at the time readings were taken, but at a slower rate than in Test #1.

Because the average space temperature was above the outlet temperature, it was concluded that there was a significant amount of "trapped" air not mixing in the air stream moving through the area. Effective temperatures were lower and the air flow per person was increased in this second test, as compared with the first.

For the following reasons, Test #2 was terminated, and a third test was initiated:

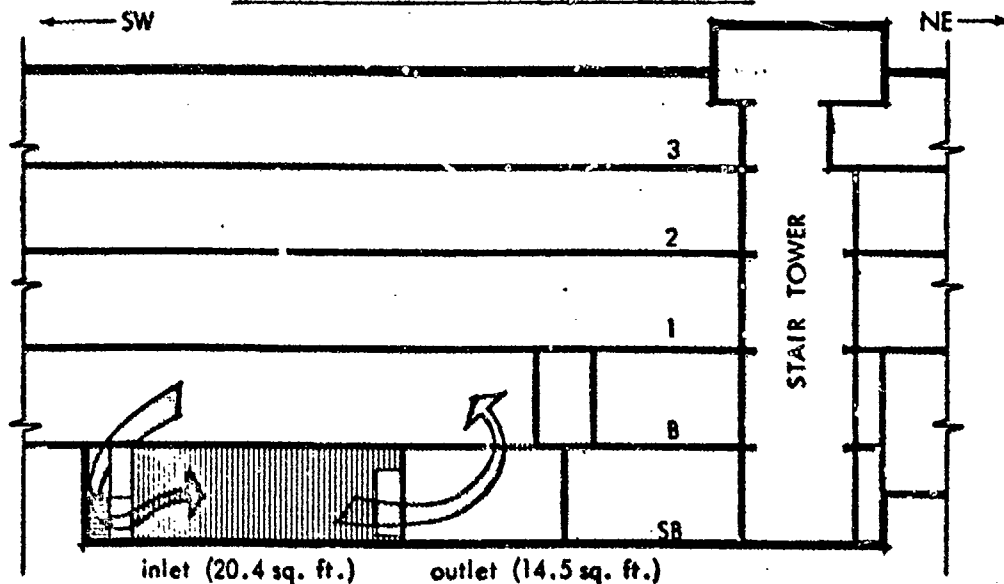
1. Time for testing was short.
2. Effective temperature was still rising.
3. Trapped air in space showed improper air mixing.

BUILDING NO. 2

TEST NO. 1

6/9/62 (1300) - 6/11/62 (1200)

150 OCCUPANTS - 10 SQ. FT. / PERSON



OUTSIDE CONDITIONS

air temperature 56 - 80F
 relative humidity 65 - 90%
 wind SW 5 mph
 comments cloudy, rain

EFFECTIVE TEMPERATURE (based on full moisture load)

ave. outlet (3' ht.) 81.5F
 ave. outlet (5' ht.) 83.0F

DRY BULB TEMPERATURE

ave. inlet (entire door) 79.3F
 ave. outlet (entire door) 83.3F
 ave. room (5' ht.) 85.0F

RATE OF AIR FLOW

cfm/person
 helium 1.9
 water vapor 6.7
 air changes/hour
 helium 1.1
 water vapor 4.0

WET BULB TEMPERATURE (based on full moisture load)

3' ht. ave. inlet 69.5F
 ave. outlet 81.5F
 5' ht. ave. inlet 70.0F
 ave. outlet 82.0F

COMMENTS

Approx. 5 lb/hr moisture input
 (token load).
 Equilibrium not established.

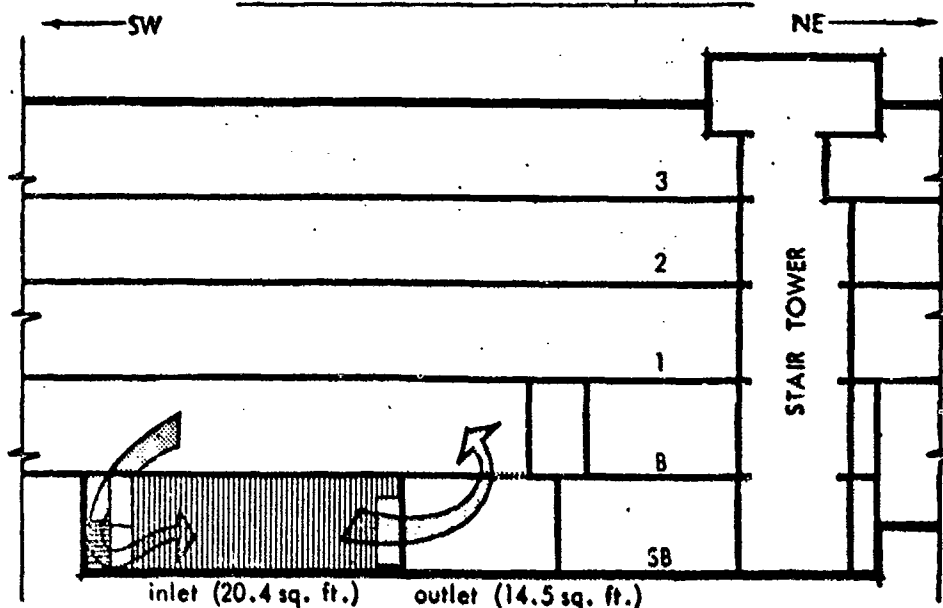
Figure 35

BUILDING NO. 2

TEST NO. 2

6/12/62 (0800) - 6/13/62 (0800)

100 OCCUPANTS - 15 SQ. FT. / PERSON



OUTSIDE CONDITIONS

air temperature 55 - 61F
 relative humidity 95%
 wind ENE 3 mph
 comments rain

EFFECTIVE TEMPERATURE (based on full moisture load)

ave. outlet (3' ht.) 81.0F
 ave. outlet (5' ht.) 82.0F

DRY BULB TEMPERATURE

ave. inlet (entire door) 78.8F
 ave. outlet (entire door) 82.8F
 ave. room (5' ht.) 84.7F

RATE OF AIR FLOW

cfm/person
 helium 3.5
 water vapor 6.3
 air changes/hour
 helium 1.3
 water vapor 2.3

WET BULB TEMPERATURE (based on full moisture load)

3' ht. ave. inlet 66.5F
 ave. outlet 80.5F
 5' ht. ave. inlet 67.5F
 ave. outlet 81.0F

COMMENTS

Approx. 5 lb/hr moisture input
 (token load).
 Equilibrium not established.

Figure 36

In Test #3 (Figure 37) half of the top panels, with a net area of 34.4 sq. ft., have been removed to increase the size of the outlet area and also to promote an increase in air mixing. The removable panels in the partition wall are illustrated (Figure 33). The outlet door still remained open to provide a total opening area of 48.9 sq. ft.

With the same occupancy as in Test #2, this test condition reached equilibrium at temperatures lower than the selected maximum. With the air change rate and space temperatures obtained, it is believed that this would be a habitable condition provided the infiltration rate of fresh air is sufficient to maintain a low CO₂ level. This has not been measured.

The reliability of the data obtained when top panels are removed is questionable. The reason for the unreliability is that psychrometers were placed in the outlet doorway rather than at the location of the outlet panels. Thus, the psychrometric data obtained at the outlet door were used to obtain the specific humidity over the entire outlet. This affects the value of calculated effective temperatures. The actual effective temperatures would be higher than the calculated values.

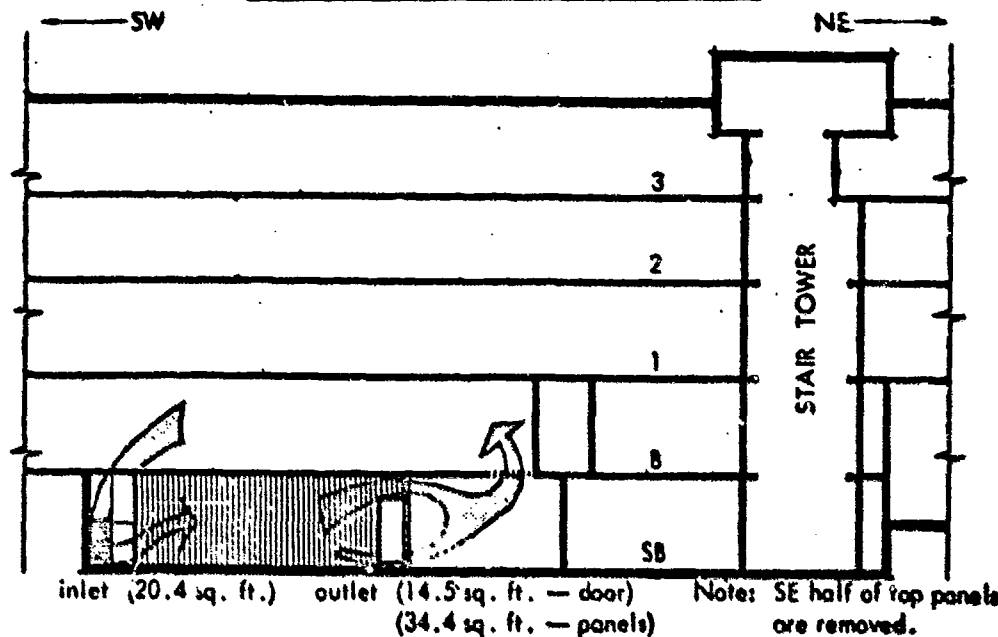
In Test #4 (Figure 38) all of the top panels were removed providing a total outlet area of 83.3 sq. ft. Occupancy remained at 15 sq. ft./person and results were not much different than in the previous test. Again, the air change rate and temperatures obtained appear to provide a habitable condition if a low CO₂ level is maintained.

BUILDING NO. 2

TEST NO. 3

6/13/62 (0900) - 6/15/62 (1000)

100 OCCUPANTS - 15 SQ. FT. / PERSON



OUTSIDE CONDITIONS

air temperature 56 - 61F
 relative humidity 84%
 wind SW 2 mph
 comments partly cloudy

EFFECTIVE TEMPERATURE (based on full moisture load)

ave. outlet (3' ht.) 74.0F
 ave. outlet (5' ht.) 77.0F

DRY BULB TEMPERATURE

ave. inlet (entire door) 76.7F
 ave. outlet (entire door) 85.0F
 ave. room (5' ht.) 83.1F

RATE OF AIR FLOW

cfm/person
 helium 6.5
 water vapor 12.8
 air changes/hour
 helium 2.4
 water vapor 4.8

WET BULB TEMPERATURE (based on full moisture load)

3' ht. ave. inlet 64.0F
 ave. outlet 67.0F
 5' ht. ave. inlet 65.3F
 ave. outlet 70.5F

COMMENTS

Approx. 5 lb/hr moisture input
 (token load).
 Equilibrium established.

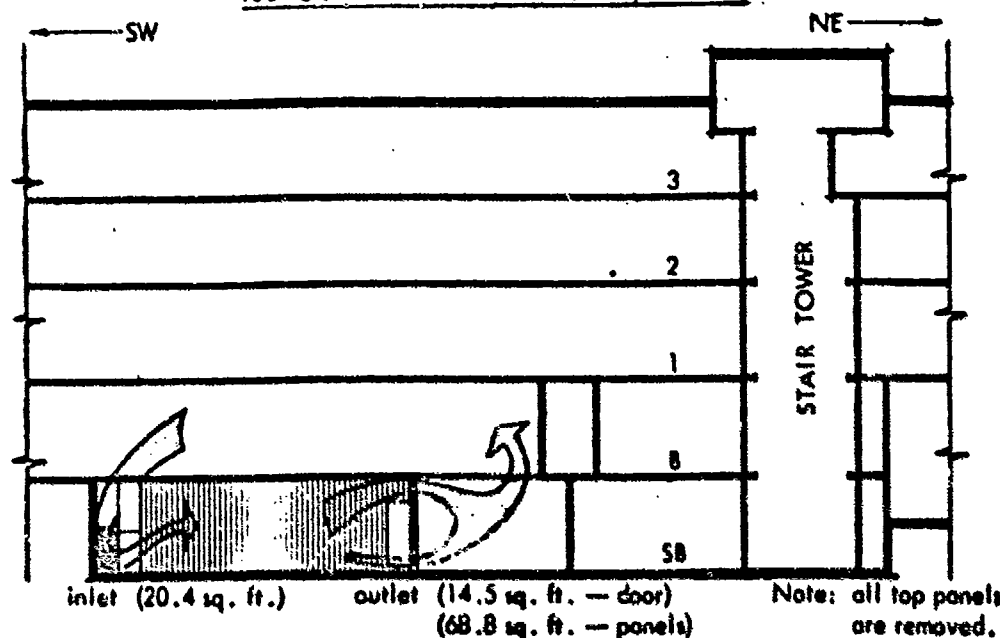
Figure 37

BUILDING NO. 2

TEST NO. 4

6/15/62 (1100) - 6/16/62 (0800)

100 OCCUPANTS - 15 SQ. FT./PERSON



OUTSIDE CONDITIONS

air temperature	59 - 64F
relative humidity	72 - 84%
wind	SW 2 mph
comments	clear, mild

EFFECTIVE TEMPERATURE (based on full moisture load)

ave. outlet (3' ht.)	76.0F
ave. outlet (5' ht.)	77.0F

DRY BULB TEMPERATURE

ave. inlet (entire door)	76.2F
ave. outlet (entire door)	83.0F
ave. room (5' ht.)	81.0F

RATE OF AIR FLOW

cfm/person	
helium	14.1
water vapor	11.8
air changes/hour	
helium	5.3
water vapor	4.4

WET BULB TEMPERATURE (based on full moisture load)

3' ht. ave. inlet	64.0F
ave. outlet	69.5F
5' ht. ave. inlet	67.2F
ave. outlet	70.0F

COMMENTS

Approx. 5 lb/hr moisture input
(token load).
Equilibrium established.

Figure 38

In Test #5 (Figure 39), occupancy was increased to about 10 sq. ft./person. All of the top panels remained open. An increased air change rate was noted and the effective temperatures again indicated habitable conditions. However, with regard to the last three tests, the method of obtaining specific humidity over the entire outlet would yield calculated effective temperatures below the actual values.

All pertinent data obtained from the five tests conducted in Building No. 2 are summarized in Table 5. The various air flow circuit configurations are also presented (Figure 40).

The problems encountered in Building No. 2 can be summarized as follows:

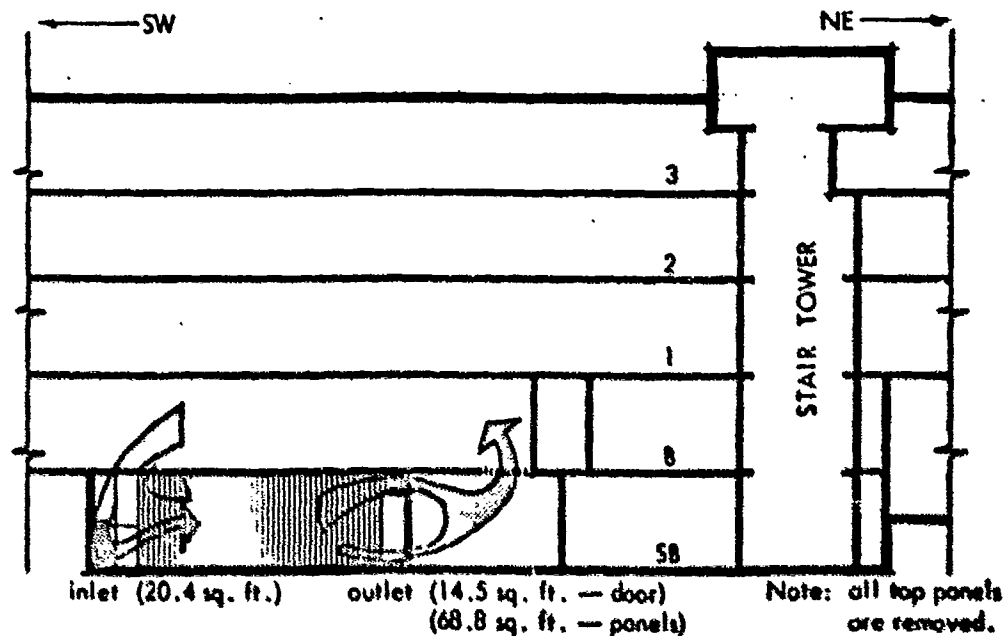
1. Time limit of 1 week in the test space imposed severe limitations.
2. Five sensing devices were acting erratically. Possibly the entire Portable Infiltration Meter system needed checking and overhauling. The erratic drifting of the instrument during the runs yielded scattered results that were not comparable to the water vapor technique. This leaves some question as to their value in this series of tests.
3. Existing mechanical equipment could not be removed from the test spaces. Moisture in the space had to be kept low to prevent damage to the equipment. Therefore, only 5 lbs. per hr. of water was evaporated instead of the amount actually required for full occupancy.

BUILDING NO. 2

TEST NO. 5

6/16/62 (0900) - 6/17/62 (0600)

150 OCCUPANTS - 10 SQ. FT. / PERSON



OUTSIDE CONDITIONS

air temperature	58 - 62F
relative humidity	75 - 84%
wind	SW 1 mph
comments	clear, mild

EFFECTIVE TEMPERATURE (based on full moisture load)

ave. outlet (3' ht.)	77.0F
ave. outlet (5' ht.)	79.0F

DRY BULB TEMPERATURE

ave. inlet (entire door)	77.7F
ave. outlet (entire door)	86.0F
ave. room (5' ht.)	83.5F

RATE OF AIR FLOW

cfm/person	
water vapor	12.3
air changes/hour	
water vapor	7.3

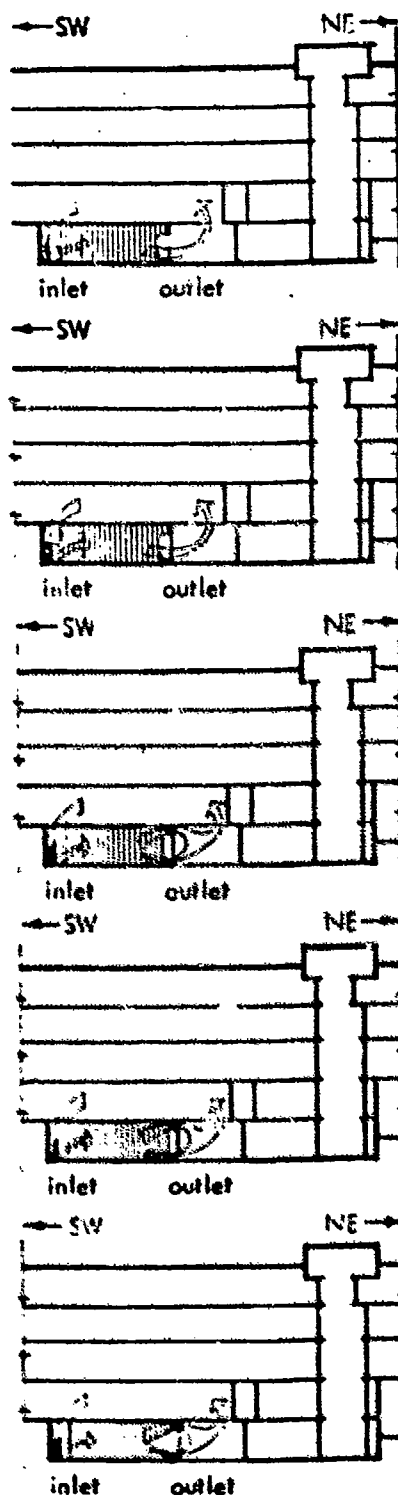
WET BULB TEMPERATURE (based on full moisture load)

3' ht. ave. inlet	64.0F
ave. outlet	71.0F
5' ht. ave. inlet	65.8F
ave. outlet	73.0F

COMMENTS

Approx. 5 lb/hr moisture input
(taken load).
Equilibrium established.

Figure 39



TEST NO. 1

Mechanical ventilation system operating.
Vol. ratio — test space to circulation space = 0.20.
Inlet opening 20.4 sq. ft.
Outlet opening 14.5 sq. ft.

TEST NO. 2

Mechanical ventilation system operating.
Vol. ratio — test space to circulation space = 0.20.
Inlet opening 20.4 sq. ft.
Outlet opening 14.5 sq. ft.

TEST NO. 3

Mechanical ventilation system operating.
Vol. ratio — test space to circulation space = 0.20.
Inlet opening 20.4 sq. ft.
Outlet opening 14.5 sq. ft. — door.
68.8 sq. ft. — SE top panels.

TEST NO. 4

Mechanical ventilation system operating.
Vol. ratio — test space to circulation space = 0.20.
Inlet opening 20.4 sq. ft.
Outlet opening 14.5 sq. ft. — door.
68.8 sq. ft. — all top panels.

TEST NO. 5

Mechanical ventilation system operating.
Vol. ratio — test space to circulation space = 0.20.
Inlet opening 20.4 sq. ft.
Outlet opening 14.5 sq. ft. — door.
68.8 sq. ft. — all top panels.

COMPARISON OF AIR FLOW CIRCUIT CONFIGURATIONS — BUILDING NO. 2

Table 5

TEST SUMMARY BUILDING NO. 2

TEST NO.	1	2	3	4	5
Duration of test	47 hrs.	24 hrs.	49 hrs.	21 hrs.	21 hrs.
Simulated occupancy	150	100	100	100	150
Floor area per person	10 sq. ft.	13 sq. ft.	15 sq. ft.	15 sq. ft.	10 sq. ft.
Outside conditions					
air temperature	56-80F	55-61F	56-61F	58-64F	58-62F
relative humidity	65-90%	95%	84%	76-84%	75-84%
wind direction	SW	ENE	SW	SW	SW
wind speed	5 mph	3 mph	2 mph	2 mph	1 mph
comments	cloudy, rain	rain	partly cloudy	clear, mild	clear, mild
Dry bulb temperature					
ave. inlet	79.3F	78.8F	76.7F	76.2F	77.7F
ave. outlet	83.3F	82.8F	85.0F	83.0F	86.0F
ave. room	85.0F	84.7F	83.1F	81.0F	83.5F
Wet bulb temperature					
ave. inlet (3')	69.5F	66.5F	64.0F	64.0F	64.0F
ave. outlet (3')	81.5F	80.5F	67.0F	69.5F	71.0F
ave. inlet (5')	70.0F	67.5F	65.3F	67.2F	65.8F
ave. outlet (5')	82.0F	81.0F	70.5F	70.0F	73.0F
Effective temperature					
ave. outlet (3')	81.5F	81.0F	74.0F	76.0F	77.0F
ave. outlet (5')	83.0F	82.0F	77.0F	77.0F	79.0F
Air flow					
cfm/person					
helium	1.9	3.5	6.5	14.1	Not used.
water vapor	6.7	6.3	12.8	11.8	12.3
air changes/hour					
helium	1.1	1.3	2.4	5.3	Not used.
water vapor	4.0	2.3	4.8	4.4	7.3
Comments	Token moisture load. Equilibrium <u>not reached.</u>	Token moisture load. Equilibrium <u>not reached.</u>	Token moisture load. Equilibrium reached.	Token moisture load. Equilibrium reached.	Token moisture load. Equilibrium reached.

CHAPTER 5

TEST BUILDING NO. 3

DESCRIPTION OF BUILDING AND TEST SPACE

The third building provided the most desirable test conditions. From the beginning of July to mid-August complete control of the building was possible. The building was unoccupied, which allowed control over window and door openings. Also, mechanical ventilation systems could be turned off at will during the six week test period.

The building selected was a 5 story dormitory 60 ft. by 180 ft. with basement (Figure 41). Main construction is reinforced concrete frame and slabs with brick panel walls, which contain about 25 percent windows. Construction throughout is at least average so that infiltration through metal windows and masonry walls is a minimum. The long axis coincides with a southeast-northwest line. Building volume is approximately 510,000 cu. ft.

The test space connects the bottom areas of both stair towers and provides a nearly straight line flow between them (Figure 42). Door openings of 17.0 sq. ft. each provide access to the 9' x 15' stair towers. Floor area of the test space is 1510 sq. ft. and the volume is 15,100 cu. ft., or 1/3 of the total basement area and basement volume respectively. The ratio of the test space volume to total building volume is approximately 3 to 100. A two-cab elevator shaft is located near the center of the test space.



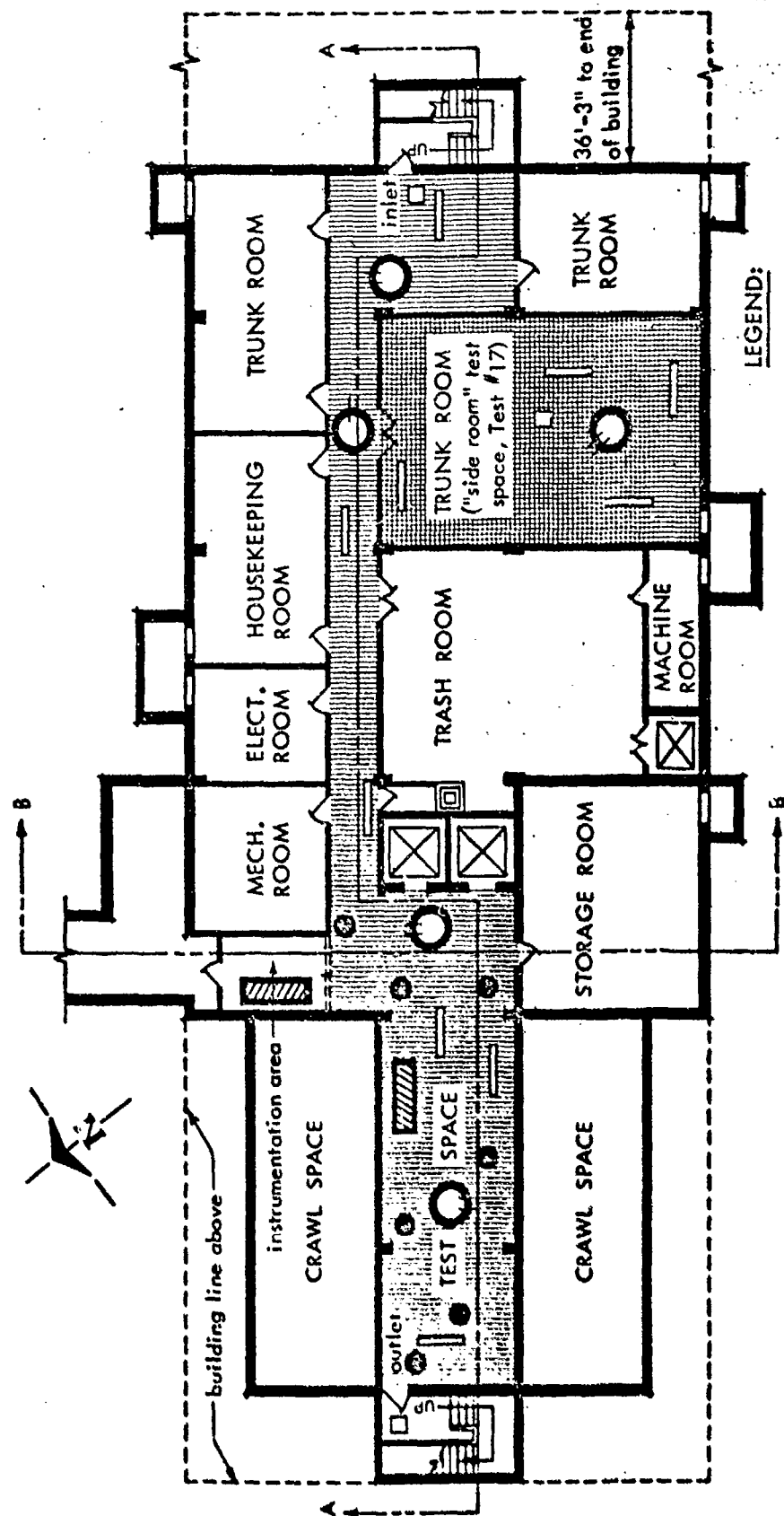
EXTERIOR VIEW — BUILDING NO. 3

Figure 41

No modification to the test space was required except to seal off an underground pipe-tunnel entering the basement. A temporary partition was also installed as shown on plan (Figure 42) to provide a separate instrumentation area. For one test, stair closures were provided in both stair towers at the second floor above ground floor. The closures were well sealed and the 5 story building then became essentially a 2 story building. In another test, a "side room" 37 ft. deep by 25 ft. wide was used. The "side room" test space had double doors in a 34.8 sq. ft. opening and was located near the cool or inlet end of the test space (Figure 42). A single high window approximately 2'-3" by 3'-2" was closed but not sealed.

The ground floor contains lobby, lounge, and office space. The four floors above contain typical dormitory rooms (Figure 43). The dormitory rooms are along the outside with 5 ft. wide corridors running along both sides of an interior service core. Room doors have a 1" crack at the bottom but no ventilation grilles in the doors.

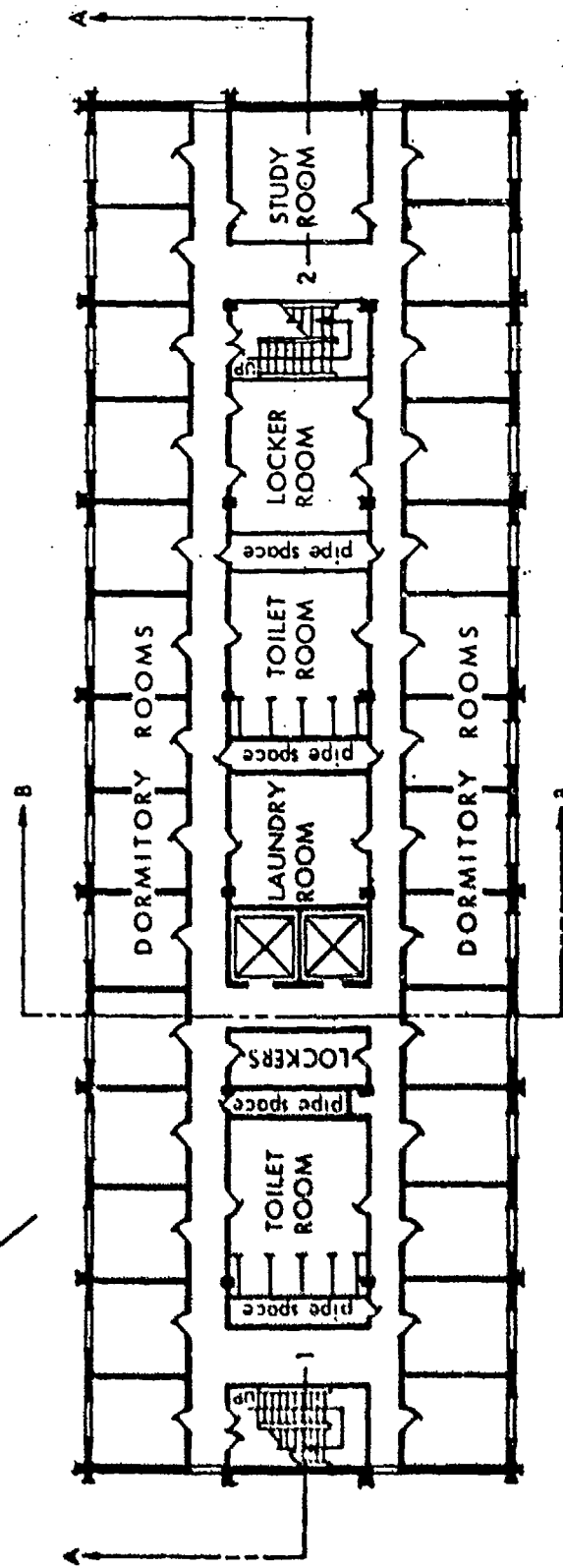
The northwest stair tower ends at the top floor while the southeast tower extends to the roof where a sun deck is located. This tower has no external walls except at the ground story. The northwest tower has one exterior wall. Exterior walls of both towers contain 11.5" wide vertical strips of windows, in units 50 inches long. Each window unit is well sealed when closed. A longitudinal section shows the stair towers and test space (Figure 44). A transverse section through the building is also presented (Figure 45).



BASEMENT PLAN SHOWING TEST SPACE - BUILDING NO. 3

Scale: 1/16" = 1'-0"

Figure 42

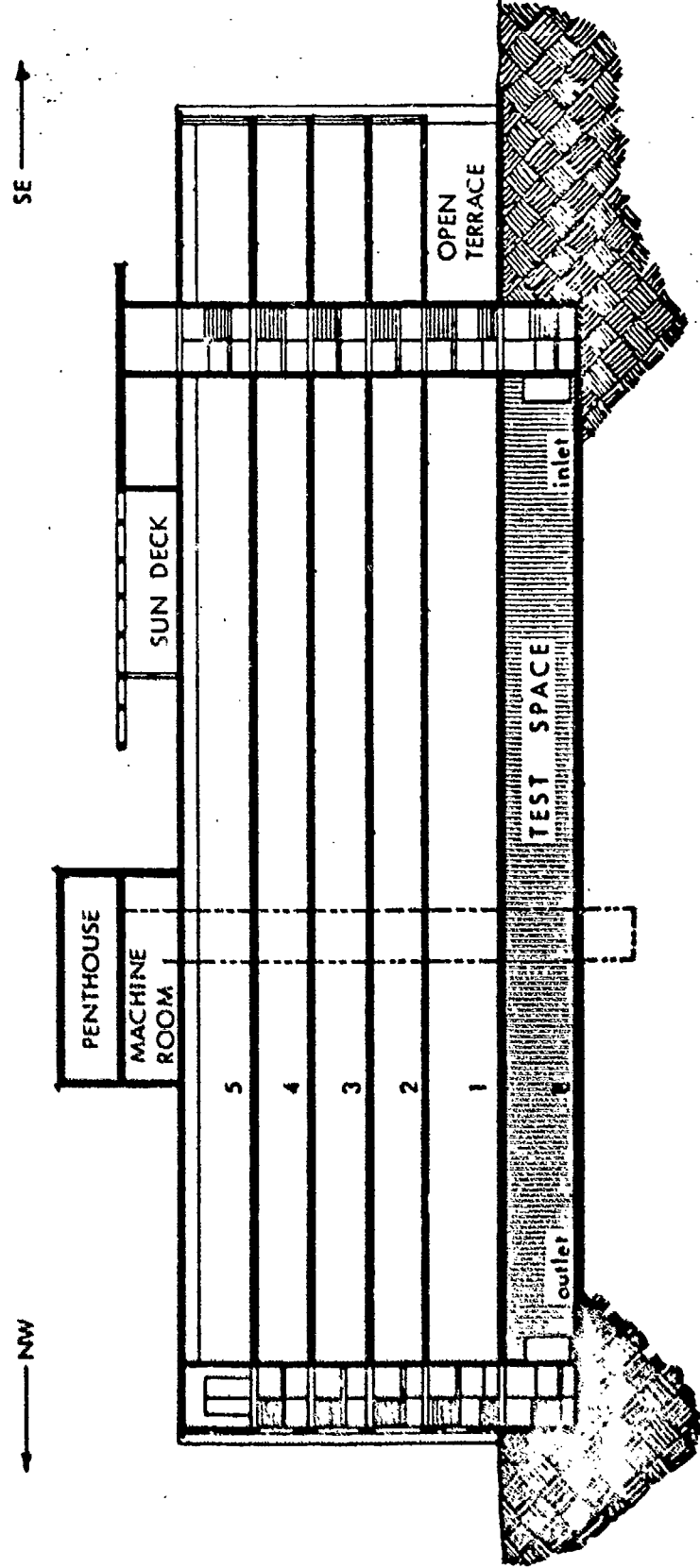


NOTE: Location of cutting plane A-A varies between points 1 and 2 from basement to penthouse in order to portray the most essential items.

TYPICAL DORMITORY FLOOR PLAN - FLOORS 2, 3, and 4 - BUILDING NO. 3

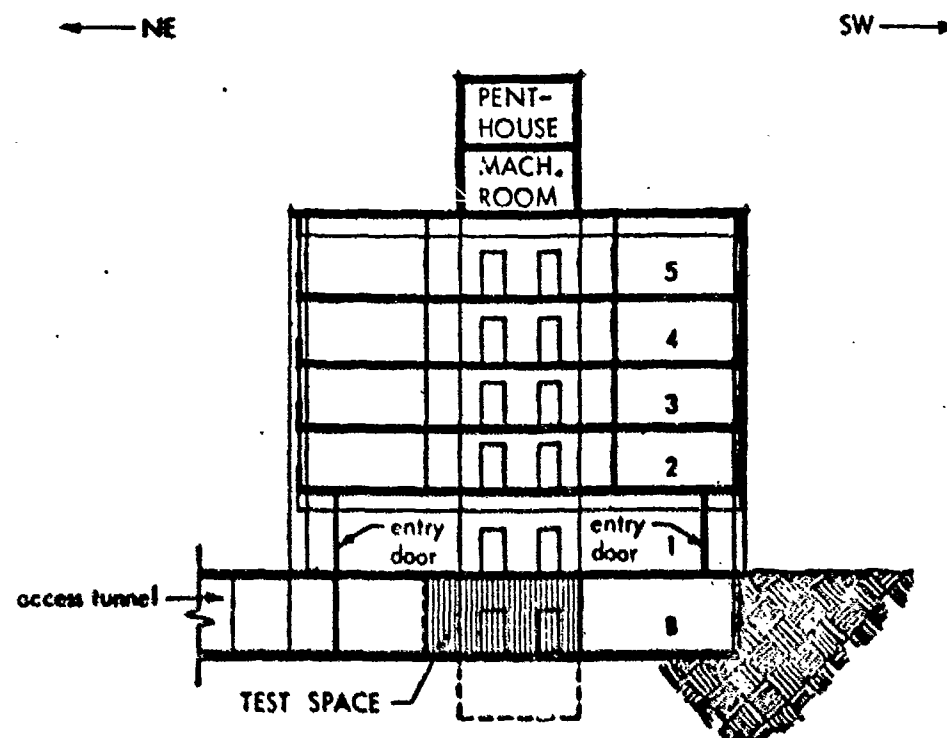
Scale: 3/64" = 1'-0"

Figure 43



SECTION A-A - BUILDING NO. 3
 Scale: 3/64" = 1'-0"

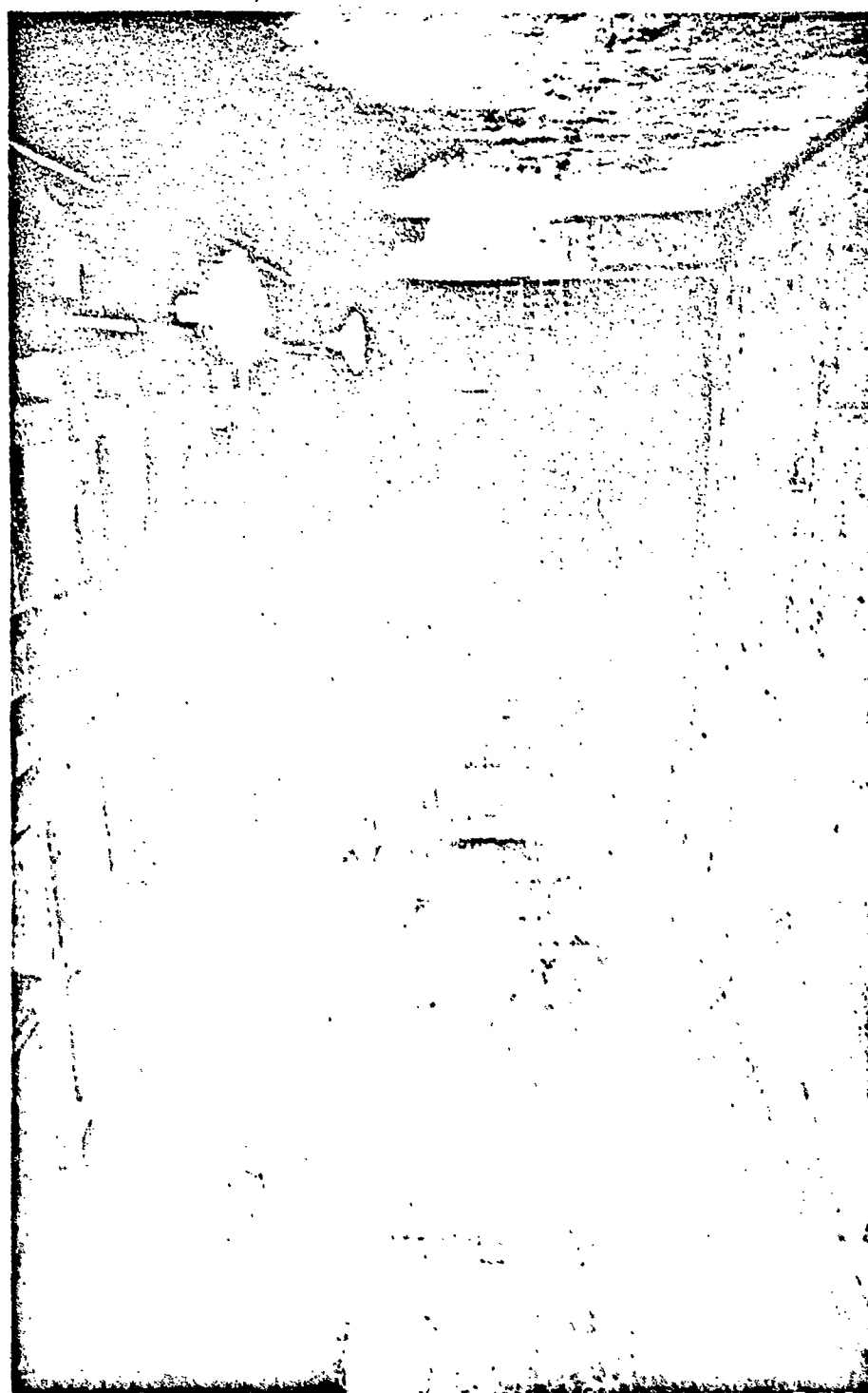
Figure 44



SECTION B-B - BUILDING NO. 3

Scale: $\frac{3}{64}'' = 1' - 0''$

Figure 45



INTERIOR VIEW OF TEST SPACE

Figure 46

An 8' x 14' section of the pipe-tunnel entrance in the basement was closed off as an instrumentation area. Potentiometers for recording thermocouple readings, timing devices, Portable Infiltration Meter indicator cabinet, and telephone were put into this area. Lamp banks, humidifier barrels, control panel, automatic psychrometers, and Portable Infiltration Meter sensing devices were located in the main test space as shown (Figure 42). An interior view of the main test space is shown (Figure 46) although the instruments were not present when the photo was taken. Paper strip indicators were located in all doorways incorporated in air flow circuits. Hygro-thermographs were located in the corridors of upper floors in the air flow circuits.

Except for the "side room" data in the last test, water vapor measurements were used to determine air change rates. The N.B.S. Portable Infiltration Meter could not be used for most tests because the air change rates were higher than the upper limit for operation. Also, erratic behavior of this instrument required that work be done to restore it to proper operating condition.

For the last test, which involved a "side room," the best Portable Infiltration Meter sensing devices were set up. The water vapor method of determining air change rate was impossible here, since there was only one opening to the "side room" test space and absolute humidity differentials could not be obtained between inlet and outlet.

Table 6

SCHEDULE OF OPERATIONS BUILDING NO. 3

TEST NO.	BEGINNING TEST DATE	TIME INTERVAL	OCCUPANCY sq. ft./person	REMARKS	AIR FLOW/ PERSON	ET at OUTLET (for full moist. load)
1	7/17/62	24 hours	(No occupants)	Windows at base of SE stair tower and top of NW stair tower open. Wind from South.	Rapid	(No occupants)
2	7/18/62	48 hours	(No occupants)	No deliberate openings except basement doors to stair towers. Checking air flow with stagnant conditions.	Negligible	(No occupants)
3	7/21/62	48 hours	(No occupants)	Stair tower doors open on top story. Mech. vent. operating.	Negligible	(No occupants)
4	7/23/62	26 hours	(No occupants)	Deliberate openings at top of both stair towers. Wind from NW. Mech. vent. operating.	Rapid	(No occupants)
5	7/24/62	46 hours	10	Stair tower doors open on top story. Taken moisture load.	15 cfm	Rising

Table 6 (Cont.)
SCHEDULE OF OPERATIONS BUILDING NO. 3

TEST NO.	BEGINNING TEST DATE	TIME INTERVAL	OCCUPANCY sq. ft./person	REMARKS	AIR FLOW/ PERSON	ET at OUTLET (for full moist. load)
6	7/26/62	27 hours	10	No deliberate openings except basement doors to stair towers. Taken moisture load.	2 cfm	79 F
7	7/27/62	68 hours	10	Stair closure 2 stories above ground floor; stair tower doors open at this level. Taken moisture load.	6 cfm	81 F
8	7/30/62	24 hours	10	Use of fan at inlet for instrument checking. Remarks same as Test #7.	(No Readings - Instrument Checking)	
9	7/31/62	16 hours	10	Same as Test #7. Larger moisture load introduced.	8 cfm	83 F
10	8/1/62	13 hours	10	Same as Test #7. Full moisture introduced.	11 cfm	84 F
11	8/3/62	24 hours	10	Stair tower doors open to top story. Full moisture introduced.	14 cfm	83 F

Table 6 (Cont.)
SCHEDULE OF OPERATIONS BUILDING NO. 3

TEST NO.	BEGINNING TEST DATE	TIME INTERVAL	OCCUPANCY sq. ft./person	REMARKS	AIR FLOW/ PERSON	ET at OUTLET (for full moist. load)
12	8/6/62	24 hours	15	Same as Test #11.	14 cfm	82 F
13	8/7/62	20 hours	20	Same as Test #11, except top story room doors open to corridors.	19 cfm	81 F
14	8/8/62	11 hours	10	Stair tower doors open on top 2 stories. Full moisture introduced. Room doors open to corridors in top 2 stories.	11 cfm	84 F
15	8/9/62	96 hours	15	Same as Test #14.	12 cfm	81 F
16	8/13/62	16 hours	10	Same as Test #14, except one window open of 4th story.	13 cfm	83 F
17	8/17/62	19 hours	20	"Side room" investigation. Full moisture load. 10 sq. ft./person in main test space and 20 sq. ft./person in "side room."	9 cfm (Values for "side room")	82 F

GENERAL PROCEDURE

Since Building No. 3 was available for a six week period and almost complete control of the building was possible, a wide variety of air flow circuits could be examined in greater detail than was possible in Buildings No. 1 and 2. A schedule of operations shown in Table 6 described the chronology of testing in Building No. 3.

The general procedure for simulating the occupants and determining air change rates which was used in Building No. 2 was also used in Building No. 3. Refer to Chapter 4. A significant difference, however, was that for the latter tests in Building No. 3 full moisture loads were used in simulating the occupants.

TEST RESULTS

Preliminary observations were made to determine the effect of extraneous factors in promoting air change in the test space after it was sealed from the remainder of the building. All cracks larger than 1/16" had been closed with tape. For this preliminary test, the basement door to each stair tower was closed.

This test made use of the tracer gas decay technique, using helium as the gas. This method here proved satisfactory as the air change rate was very low. The air change rate, however, was not constant over the extended period of test time necessary for testing, but could be judged to be less than 0.3 air change per hour at the maximum. This rate proved to be negligibly

small in comparison with rates obtained later under better flow conditions.

Preliminary observations indicated that, for the remainder of the tests conducted in this test space, no concern need be given to extraneous factors affecting the results. The taping had reduced these effects to a tolerable minimum.

Not all of the test runs shown in Table 6, Schedule of Operations Building No. 3, are reported in detail. The reason for this is that some test runs gave no significant results, and in some other tests the data was later proved to be invalid. One test was set up only for purposes of instrument checking. These tests have been included in the schedule of operations so that the chronological order of testing would be complete.

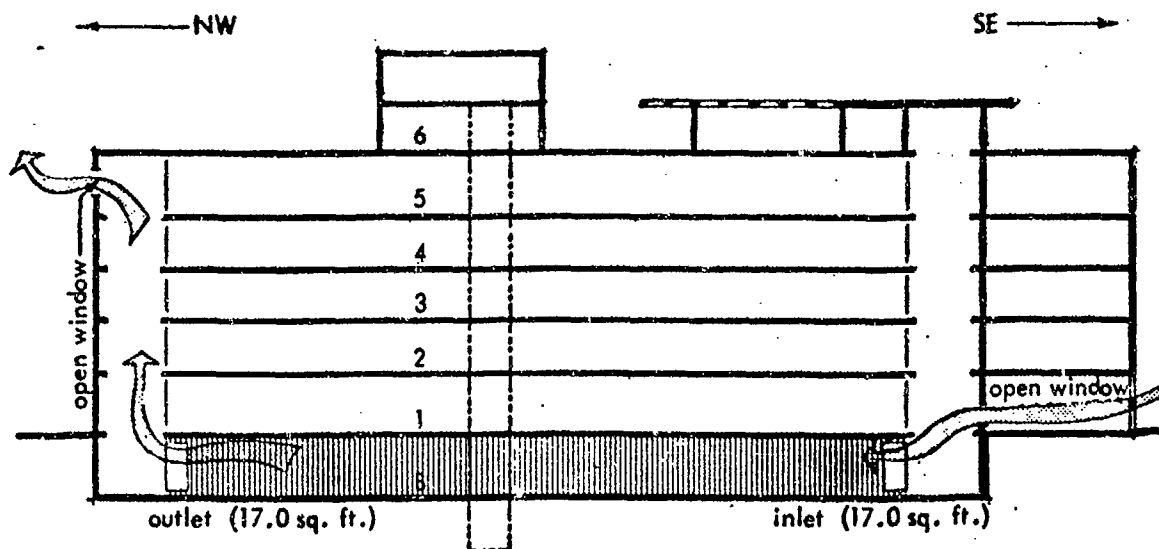
Tests #1 and #4 (Figures 47 and 48) were conducted to determine what air change rates might be expected in the test space when various openings to the atmosphere were made in the air flow circuit. One window unit of 4.0 sq. ft. was open in each stair tower as shown on the figures. The air change rates were mainly dependent on external wind conditions, and therefore, the results of the few tests run under these conditions could not be correlated. No accurate measurement of these air change rates could be made at this time because of the unsteadiness of the air flow and the fact that all air change rates were too large for the tracer gas decay method to give accurate records.

BUILDING NO. 3

TEST NO. 1

7/17/62 (0800) - 7/18/62 (1700)

NO OCCUPANTS



OUTSIDE CONDITIONS

air temperature	66 - 82F
relative humidity	50 - 90%
wind	S 3-5 mph
comments	cloudy, humid

EFFECTIVE TEMPERATURE
(based on full moisture load)

ave. outlet (3' ht.)	$\frac{e}{*}$
ave. outlet (5' ht.)	$\frac{*}{*}$

DRY BULB TEMPERATURE

ave. inlet (entire door)	70.0F
ave. outlet (entire door)	71.0F
ave. room (5' ht.)	73.2F

RATE OF AIR FLOW

cfm/person	$\frac{*}{*}$
air changes/hour	rapid

WET BULB TEMPERATURE
(based on full moisture load)

3' ht. ave. inlet	$\frac{*}{*}$
ave. outlet	$\frac{*}{*}$
5' ht. ave. inlet	$\frac{*}{*}$
ave. outlet	$\frac{*}{*}$

COMMENTS

* No occupants.

Figure 47

From these tests, however, it was observed that if it were possible to make openings to the atmosphere at selected points in the air flow circuit, with anything but completely calm ambient wind conditions, the test space could possibly be used without giving consideration to the driving force created by the occupancy in the space. The air which would flow through the test space would be almost completely fresh air, and unless the ambient conditions were unfavorable with very high temperature and humidity, conditions in the space would be good. The problems that arise in the case of air circulating through an enclosed circuit in the building, constantly rising temperature, humidity, and CO₂ content of the inlet air, would not occur. The problem of dissipating the excess heat and humidity by infiltration and condensation in that part of the air flow circuit outside the test space would not arise.

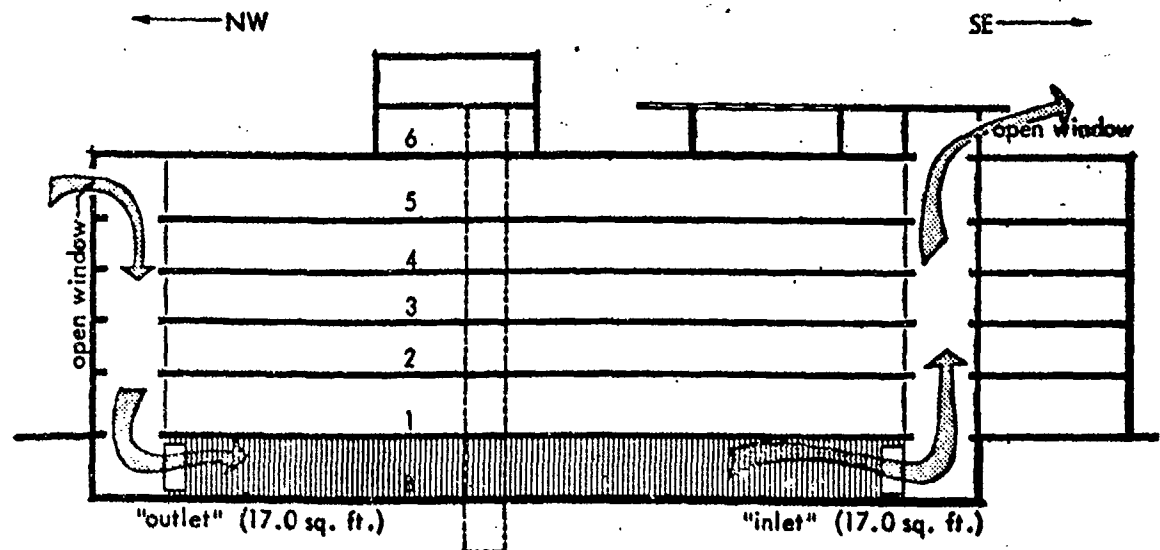
It was not considered necessary to continue testing this type of air flow circuit with simulated occupancy because of the good conditions which prevailed with the space unoccupied. Any additional heat or moisture would necessarily increase or add to the driving force of the wind, although it would not be likely to change it to any great extent. The only possible drawback in this case would be that in cool weather the test space might become too cold for continuous occupation.

BUILDING NO. 3

TEST NO. 4

7/23/62 (1000) - 7/24/62 (1200)

NO OCCUPANTS



OUTSIDE CONDITIONS

air temperature 61 - 78F
 relative humidity 70 - 95%
 wind NW 7 mph
 comments showers

EFFECTIVE TEMPERATURE
 (based on full moisture load)

ave. outlet (3' ht.) $\frac{\bullet}{\bullet}$
 ave. outlet (5' ht.) $\frac{\bullet}{\bullet}$

DRY BULB TEMPERATURE

ave. inlet (entire door) 70.5F
 ave. outlet (entire door) 67.0F
 ave. room (5' ht.) 72.5F

RATE OF AIR FLOW

cfm/person $\frac{\bullet}{\bullet}$
 air changes/hour rapid

WET BULB TEMPERATURE
 (based on full moisture load)

3' ht. ave. inlet $\frac{\bullet}{\bullet}$
 ave. outlet $\frac{\bullet}{\bullet}$
 5' ht. ave. inlet $\frac{\bullet}{\bullet}$
 ave. outlet $\frac{\bullet}{\bullet}$

COMMENTS

"Outlet" and "inlet" indicate locations, not direction of air flow.
 • No occupants.

Figure 48

Test #6 (Figure 49) was one of the first of the series in the test with simulated occupants. The basement access doors into the stair tower were open, but otherwise the stair towers were closed off from the remainder of the building. All fresh air would necessarily have to infiltrate into the stair towers from the outside, or from the interior of the building around the stair tower doors at each floor level. This amount of infiltration was not expected to be large in comparison with that necessary to sustain required conditions in the basement test space. This expectation was borne out in the results. The pattern of air change showed that the lighter heated air in the test space was displaced by the heavier cooler air in the stair tower. This resulted in air change occurring mainly near the stair tower doors with little change occurring in the interior of the test space. The pattern of the air current is shown in the figure.

The air change rate in the test space for the condition, found by both tracer gas decay and water vapor methods, was on the order of only one air change per hour or only about 2 cfm per person for this occupancy. The amount of clean outside air that had infiltrated into the building is not known. The air could very well lose the excess heat from the basement by condensation through the stair tower wall, but the CO_2 content in the air could be continually increasing. Also, the full moisture load for 150 people in the basement was not added to the space. If this moisture load had been added, for this low air change rate, conditions in the basement would very quickly have become intolerable and the maximum allowable effective temperature surpassed.

This test is comparable in conditions to previous tests made in Building No. 1, where the air change rate was found to be fairly high. This was most likely due to the fact that mechanical ventilation was operating in that test. The time of year and the ambient weather conditions were also quite different, but this is not thought to have caused a change of this magnitude.

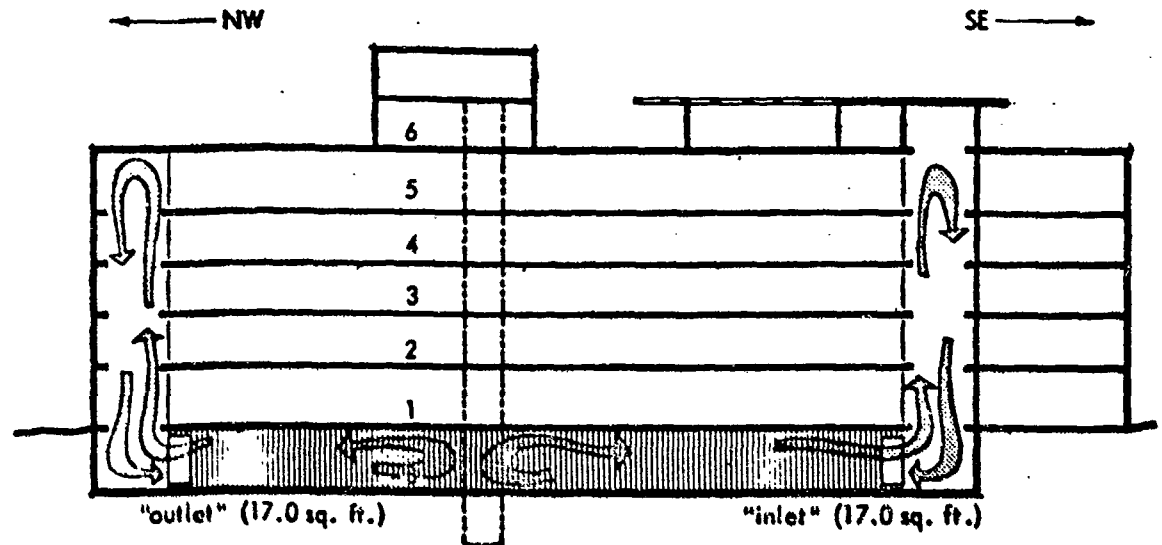
At any rate, this condition of operation at this time of year was seen to be poor, and an air flow circuit of this type encountered in any potential shelter space would definitely not be adequate.

BUILDING NO. 3

TEST NO. 6

7/26/62 (1100) - 7/27/62 (1400)

150 OCCUPANTS - 10 SQ. FT. / PERSON



OUTSIDE CONDITIONS

air temperature	50 - 69F
relative humidity	45 - 85%
wind	SW 2-4 mph
comments	cloudy, cool

DRY BULB TEMPERATURE

ave. inlet (entire door)	77.0F
ave. outlet (entire door)	79.0F
ave. room (5' ht.)	83.6F

WET BULB TEMPERATURE (based on full moisture load)

3' ht. ave. inlet	62.5F
ave. outlet	76.0F
5' ht. ave. inlet	64.5F
ave. outlet	82.0F

EFFECTIVE TEMPERATURE (based on full moisture load)

ave. outlet (3' ht.)	76.0F sat.
ave. outlet (5' ht.)	82.0F sat.
both readings beyond saturation point	

RATE OF AIR FLOW

cfm/person	2
air changes/hour	1 to 1.5

COMMENTS

Approx. 5 lb/hr moisture input (token load).
Equilibrium established.
At full moisture input saturation would have been reached.
"Outlet" and "inlet" indicate locations, not direction of air flow.

Figure 49

Tests #7, #9, and #10 (Figures 50, 51, and 52) were conducted during a one week period when ambient weather conditions were relatively constant. For this series of tests a closure was placed in both stair towers between the second and third stories of the building, essentially reducing the building to a 2 story-plus-basement configuration.

The simulated occupancy of the basement was based on a 10 sq. ft. per person area requirement. The expected average test space dry bulb temperature was judged to be between 80 F and 85 F; therefore, the ratio of sensible to latent heat input was set at one to one on the basis of Table 1. However, as the effect of a high moisture load on the building could not be foreseen exactly, only a portion of the total amount required was added in the first test and an attempt was made to predict a final condition of full input from the results obtained in this manner.

The air flow circuit as initially set up had little direct contact with any exterior surface of the building. The circuit through the second floor consisted only of the hallways in the interior of the building. No doors to the dormitory rooms were opened. Air movement through openings around the doors would provide the only contact between the high temperature, high humidity air and the ambient room air adjacent to the cool exterior walls.

In Test #7 (Figure 50) provision was made for a moisture input to the test space of approximately 5 pounds per hour, actual full occupancy requirement for the space was approximately 28 pounds per hour. The test was conducted

over a three day period and at no time did the actual effective temperature in the test space approach the maximum allowable of 85 F.

The air change rate for this condition was determined by the water vapor method and was found to average between 3 and 4 air changes per hour after equilibrium had been reached. When the effective temperature was projected to include the effects of a full moisture addition in the test space, it was still well below the maximum allowable. The projected effective temperature was between 81 F and 81.5 F.

Projecting the effects of the full complement of moisture addition in the space assumes that the air change rate and dry bulb temperature of the space would not be affected by the actual addition of the full latent load to the space. Only the outlet humidity is considered to be affected. The resulting relative humidity and effective temperature are based on the same maximum dry bulb temperature.

In Test #9 (Figure 51), the second of this series, the amount of moisture input was doubled since in the previous test there was no apparent condensation of water vapor on the surfaces of the air flow circuit.

The air change rate for this condition of sensible and latent heat addition rose to 4.5 to 5 air changes per hour. The condition of occupancy had not been changed from the previous test condition of approximately 10 sq. ft. per person, except for the addition of a greater amount of latent heat input. The addition of this increased moisture load seemed to have more

effect on the final condition of dry bulb temperature than had been expected. The average dry bulb temperature in the test space rose over 2 degrees F, even with the increase in air change rate. This rise might be partially explained by different ambient conditions, but these conditions, at least as far as temperature is concerned, did not vary to any extent from those of the previous test. The ambient relative humidity did increase and this could cause a higher relative humidity inside the test space and, therefore, a higher effective temperature. The projected effective temperature for full moisture load did rise, in fact, reaching 83 F to 84 F.

However, the total effect of the increase in the amount of latent heat addition was not what had been anticipated. For this reason, it was decided that in order to ascertain with the greatest degree of reliability the final conditions of air flow and effective temperature in the space, the full latent load should be added to the test space. This would entail the possibility of damaging the building or its contents, and this factor would also have to be considered.

In Test #10 (Figure 52), the third test of this building configuration, the full amount of latent load was added to the test space. The sensible load remained the same as in the two preceding Tests, #7 and #9.

Equilibrium was never established in Test #10. The ambient conditions were practically the same as they were for the first test of this configuration, although the results were much different. It becomes evident, then that

these different results must have been caused by the addition of the greater amount of moisture. Within a 12 hour period after the start of the full moisture addition, the effective temperature in the space had risen to 85 F and condensation was occurring on the cooler walls and windows throughout the air flow circuit. The air change rate calculated by the water vapor method was apparently about 9 per hour, which is double what was found in Test #7. This increase would be partly due to the fact that the temperature in the test space was much higher and, therefore, the driving force was higher. Most likely, though, there is an error due to the fact that equilibrium had not been reached. The relative humidity in the test space was continually rising throughout the duration of this test so that the vapor pressure in the space was continually increasing. This would cause a greater amount of water vapor to enter the surfaces of the test space and accordingly a smaller amount would remain in the air. For the same rate of moisture addition to the space, a smaller apparent increase in the vapor content of the air would indicate a larger air change rate, in this case larger than was really occurring. The actual rate was more likely 6 to 7 air changes per hour.

During this test the ratio of sensible to latent heat was not changed from the conditions of the previous tests to account for the increase in the test space temperature. However, the input remained close enough to that required so that the results can be considered valid. An increase in the amount of latent heat combined with a decrease in sensible heat would

likely result in a lower air change rate and a much greater relative humidity.

Since the relative humidity in the space was already over 90%, this in effect would cause the condition in the space to become worse, approaching 100% relative humidity with condensation on the surfaces of the test space which would continue for the duration of the occupancy.

It was very apparent at this time that an air flow circuit of this type was not practical, at least where only a limited area of wall and window surface directly connected with the ambient air was available. The results would undoubtedly have been improved for a time had the dormitory room doors been opened and a larger amount of window and wall space been made available for condensation and exfiltration of moisture laden air. The main result obtained from these tests is that the projection of final conditions by the use of only a portion of the total moisture load in the actual test should be considered. Only the addition of the full complement of latent and sensible heat to simulate the desired occupancy will give accurate results. This procedure was adopted in the remainder of the tests in this building.

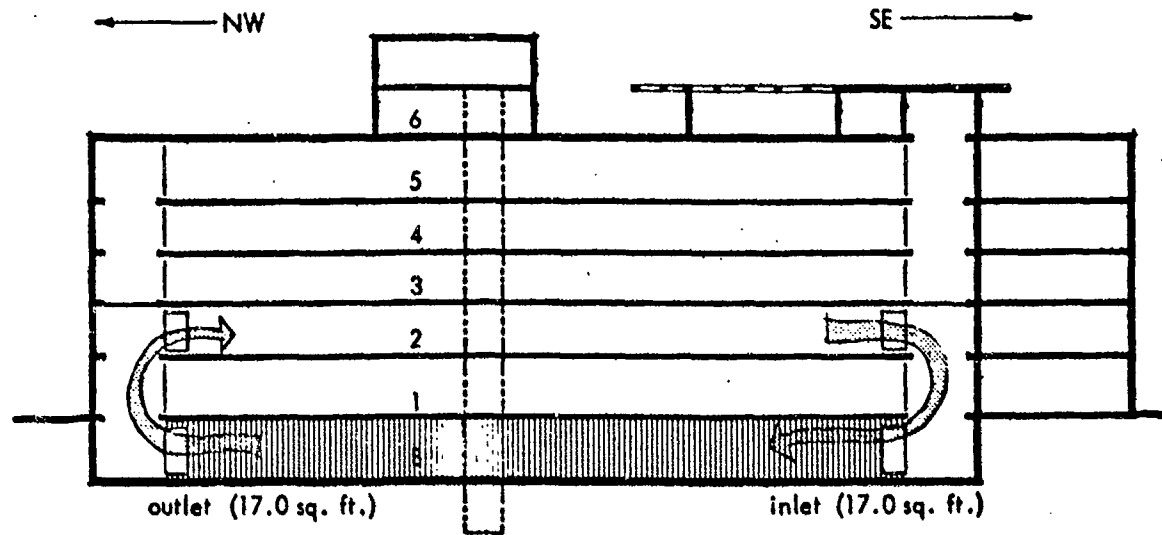
These three tests (#7, #9, and #10) show why the results for Test #5 are invalid to a certain extent, and why it has been omitted from the discussion.

BUILDING NO. 3

TEST NO. 7

7/27/62 (1400) - 7/30/62 (1000)

150 OCCUPANTS - 10 SQ. FT. / PERSON



OUTSIDE CONDITIONS

air temperature 60 - 81F
 relative humidity 30 - 80%
 wind S 3-5 mph
 comments warm, sunny

EFFECTIVE TEMPERATURE (based on full moisture load)

ave. outlet (3' ht.) 81.0F
 ave. outlet (5' ht.) 81.5F

DRY BULB TEMPERATURE

ave. inlet (entire door) 74.0F
 ave. outlet (entire door) 81.0F
 ave. room (5' ht.) 81.6F

RATE OF AIR FLOW

cfm/person 5 to 7
 air changes/hour 3 to 4

WET BULB TEMPERATURE (based on full moisture load)

3' ht. ave. inlet 63.8F
 ave. outlet 78.5F
 5' ht. ave. inlet 63.8F
 ave. outlet 79.2F

COMMENTS

Approx. 5 lb/hr moisture input
 (token load).
 Equilibrium established.
 No apparent condensation.

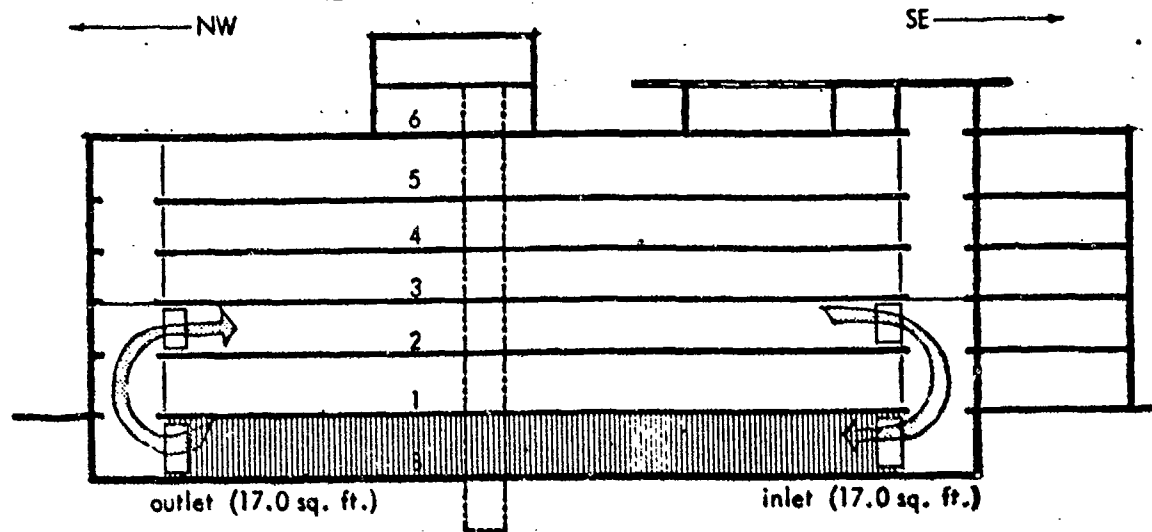
Figure 50

BUILDING NO. 3

TEST NO. 9

7/31/62 (1700) - 8/1/62 (0900)

150 OCCUPANTS - 10 SQ. FT. / PERSON



OUTSIDE CONDITIONS

air temperature 60 - 78F
relative humidity 50 - 80%
wind W 3 mph
comments clear, hot

EFFECTIVE TEMPERATURE (based on full moisture load)

ave. outlet (31 ht.) 63.0F
ave. outlet (5' ht.) 84.5F

DRY BULB TEMPERATURE

ave. inlet (entire door) 76.5F
ave. outlet (entire door) 85.9F
ave. room (5' ht.) 83.9F

RATE OF AIR FLOW

cfm/person 8
air changes/hour 4.5 to 5

WET BULB TEMPERATURE (based on full moisture load)

3' ht. ave. inlet 71.5F
ave. outlet 81.0F
5' ht. ave. inlet 71.5F
ave. outlet 82.5F

COMMENTS

9.7 lb/hr moisture input
(partial load).
Equilibrium established.
No condensation apparent.

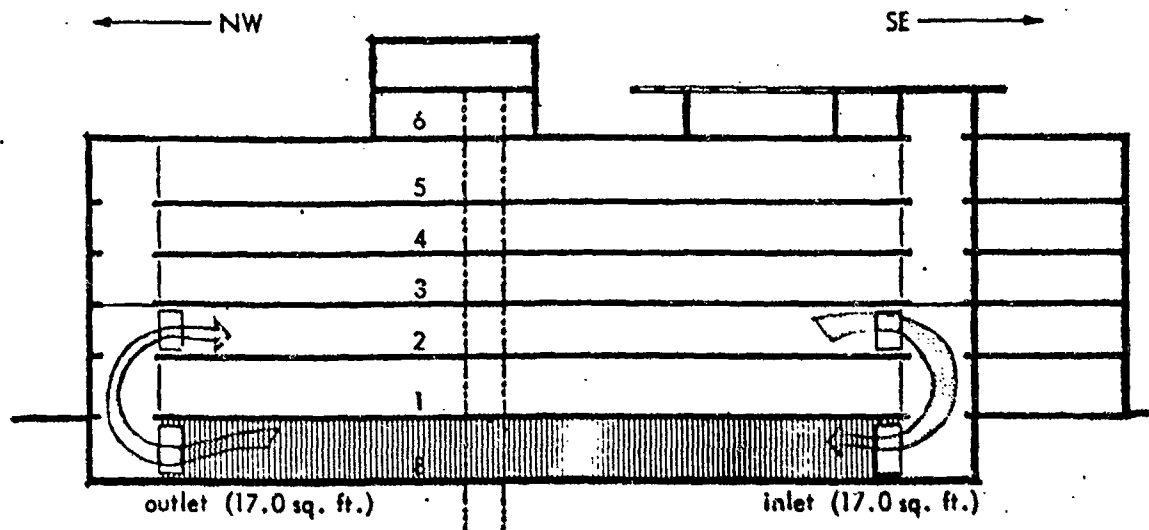
Figure 51

BUILDING NO. 3

TEST NO. 10

8/1/62 (0900) - 8/1/62 (2200)

150 OCCUPANTS - 10 SQ. FT. / PERSON



OUTSIDE CONDITIONS

air temperature	68 - 80F
relative humidity	30 - 46%
wind	NW 3 mph
comments	clear, hot

EFFECTIVE TEMPERATURE (based on full moisture load)

ave. outlet (3' ht.)	84.0F
ave. outlet (5' ht.)	84.5F

DRY BULB TEMPERATURE

ave. inlet (entire door)	77.2F
ave. outlet (entire door)	86.4F
ave. room (5' ht.)	84.8F

RATE OF AIR FLOW

cfm/person	10 to 12
air changes/hour	6 to 7

WET BULB TEMPERATURE (based on full moisture load)

3' ht. ave. inlet	77.5F
ave. outlet	83.0F
5' ht. ave. inlet	78.0F
ave. outlet	84.0F

COMMENTS

29 lb/hr moisture input
(full load).
Equilibrium not established.
Condensation on second
story within 12 hours.

Figure 52

For Test #11 (Figure 53) a different building configuration was used. The change made between the conditions of this test and those of the previous series of tests was the increase in height of the air flow circuit from two to five stories. The conditions in the test space were continued as in Test #10. The same amount of moisture input was made, but the sensible load was somewhat greater than required. However, the effects of change in height would still be expected to become apparent when the results of this test were compared with those of the previous tests, considering the fact that the changes in ambient conditions were not extensive.

Upon comparison with the previous test, it is evident that the dry bulb temperature throughout the test space showed very little change. The air change rate was increased, reaching 7 to 9 air changes per hour, as was to be expected from the additional height. This increase was not large, however, as the air change rate in the previous test was about 6 to 7 air changes per hour. The main difference in the two tests is noted in the relative humidity and effective temperature comparisons. In the previous test, effective temperatures had quickly reached 85 F and the relative humidity in the test space was over 90% with both continuing to rise when the test was halted. In this test, equilibrium was reached at lower figures. Since the dry bulb temperature throughout the test space did not change appreciably, these differences in results obviously came about as a result of decreased relative humidity in the test space.

The relative humidity in the space during this period did not exceed 85%, and at most times was between 70% and 80%. The more favorable results were due to the increased amount of cooler surface which was available for condensation of the water vapor from the air. The available surface was more than doubled by the increase in length of the air flow circuit. While conditions in the test space were still not as good as desired, evidently this was a step in the right direction. Using all available cool surfaces to condense water vapor from the air is very desirable. Most condensation was occurring on the windows of the stair towers, in particular on those of the inlet stair tower which were the coolest surfaces at all times during the testing.

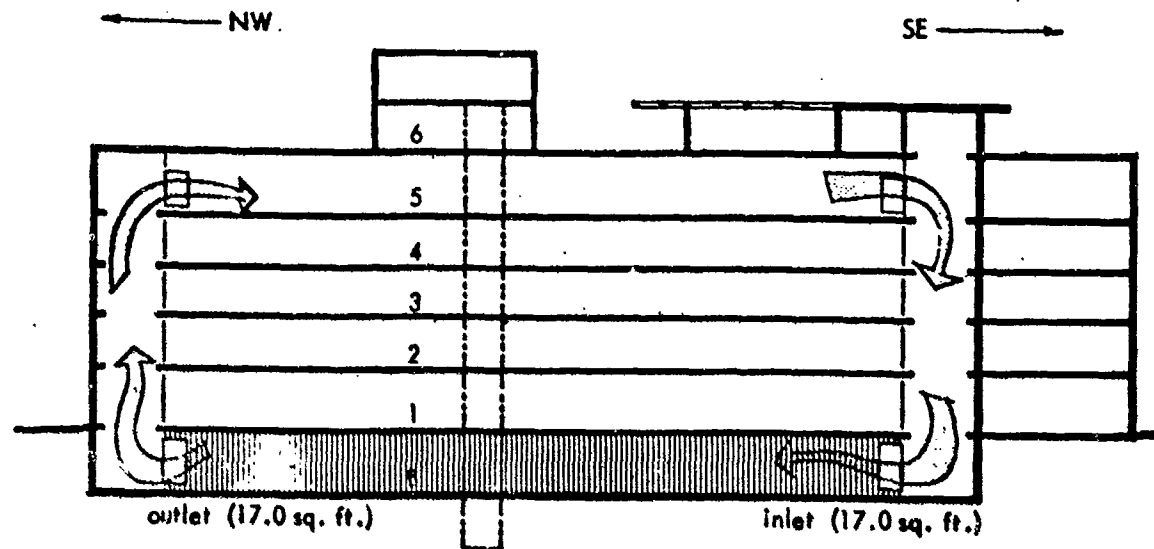
When large amounts of condensation occur outside the test space, in amounts nearly equaling the amount added to the space, inlet conditions to the space will not be substantially affected and equilibrium conditions will be established. However, as was noted in Test #10, when this amount of condensation does not occur, the inlet humidity will be continually increasing and there is no hope that equilibrium can be reached.

BUILDING NO. 3

TEST NO. 11

8/3/62 (1200) - 8/4/62 (1730)

150 OCCUPANTS - 10 SQ. FT. / PERSON



OUTSIDE CONDITIONS

air temperature 67 - 80F
relative humidity 40 - 74%
wind S 2-5 mph
comments clear, hot

EFFECTIVE TEMPERATURE (based on full moisture load)

ave. outlet (3' ht.) 83.0F
ave. outlet (5' ht.) 84.5F

DRY BULB TEMPERATURE

ave. inlet (entire door) 77.7F
ave. outlet (entire door) 86.4F
ave. room (5' ht.) 84.5F

RATE OF AIR FLOW

cfm/person 12 to 15
air changes/hour 7 to 9

WET BULB TEMPERATURE (based on full moisture load)

3' ht. ave. inlet 74.0F
ave. outlet 81.0F
5' ht. ave. inlet 74.0F
ave. outlet 83.0F

COMMENTS

26 lb/hr moisture input
(full load).
Equilibrium established.
Condensation apparent.

Figure 53

Another method which would seem to be available for creating better conditions, along with the increase in cool surface area, would be to decrease the amount of latent heat addition in the test space. This would, in effect, be accomplished only by decreasing the simulated occupancy in the space. This was the method adopted for the next test.

For Test #12 (Figure 54) the configuration of the air flow circuit was not changed from what it had been in the previous test. The purpose of this test was to determine the effect of reduced occupancy on air change rate and space conditions. The latent and sensible heat additions were adjusted to simulate an actual occupancy of approximately 100 people in the test space which amounted to 15 sq. ft. of floor space per person.

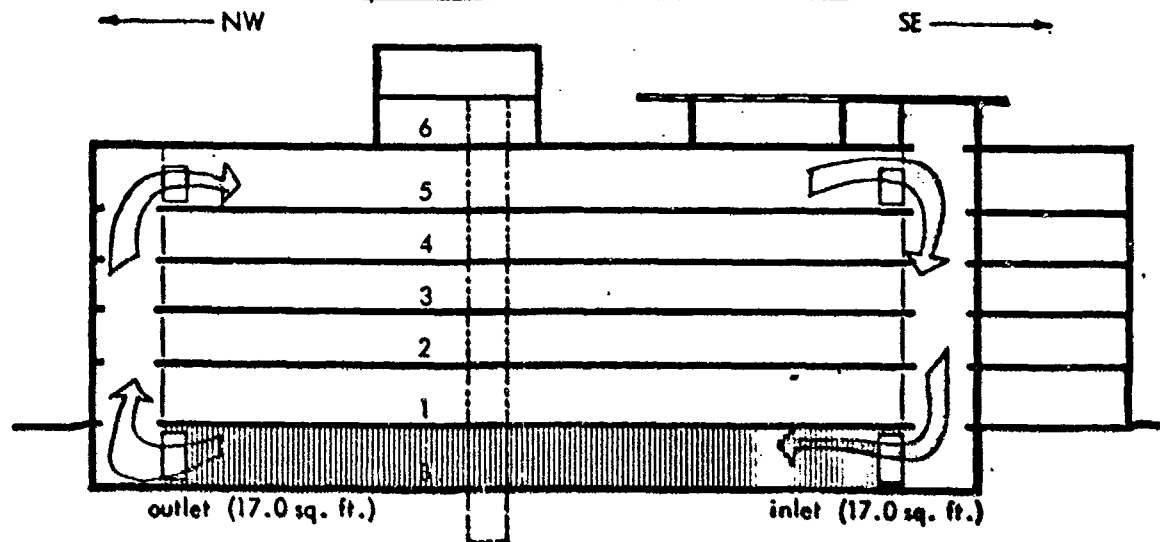
The air change rate through the space dropped to between 5 and 6 air changes per hour and the average dry bulb temperature in the test space dropped to about 83 F, although the ambient outside temperature during this test was higher than in any previous test. The effective temperature at a 3 ft. height did not exceed 82 F during this test, which would indicate that a lower standard of occupancy might be helpful in critical locations to attain better space conditions. It should be noted that although the air change rate decreased from the previous test, due to the fact that the occupancy was lower, a larger flow of air per person was obtained (Figure 54).

BUILDING NO. 3

TEST NO. 12

8/6/62 (1400) - 8/6/62 (2200)

100 OCCUPANTS - 15 SQ. FT. / PERSON



OUTSIDE CONDITIONS

air temperature 75 - 92F
 relative humidity 40 - 80%
 wind S 6 mph
 comments hot

EFFECTIVE TEMPERATURE (based on full moisture load)

ave. outlet (3' ht.) 82.0F
 ave. outlet (5' ht.) 82.8F

DRY BULB TEMPERATURE

ave. inlet (entire door) 77.8F
 ave. outlet (entire door) 84.1F
 ave. room (5' ht.) 83.2F

RATE OF AIR FLOW

cfm/person 13 to 15
 air changes/hour 5 to 6

WET BULB TEMPERATURE (based on full moisture load)

3' ht. ave. inlet 74.0F
 ave. outlet 80.0F
 5' ht. ave. inlet 74.2F
 ave. outlet 82.0F

COMMENTS

18.4 lb/hr humidity input
 (near full load).
 Equilibrium reached.

Figure 54

It would seem possible in looking at the results of Test #12 to reach a point of simulated occupancy which would not create a sufficient driving force to give the air change rate necessary for the number of occupants in the test space. In Test #13 (Figure 55) the simulated occupancy was decreased to about 75 persons amounting to 20 sq. ft. of floor space per person. It was also decided to use more available wall and window space for condensation during this test. For this reason, the top floor doors of the dormitory rooms were now opened, greatly increasing the available window area.

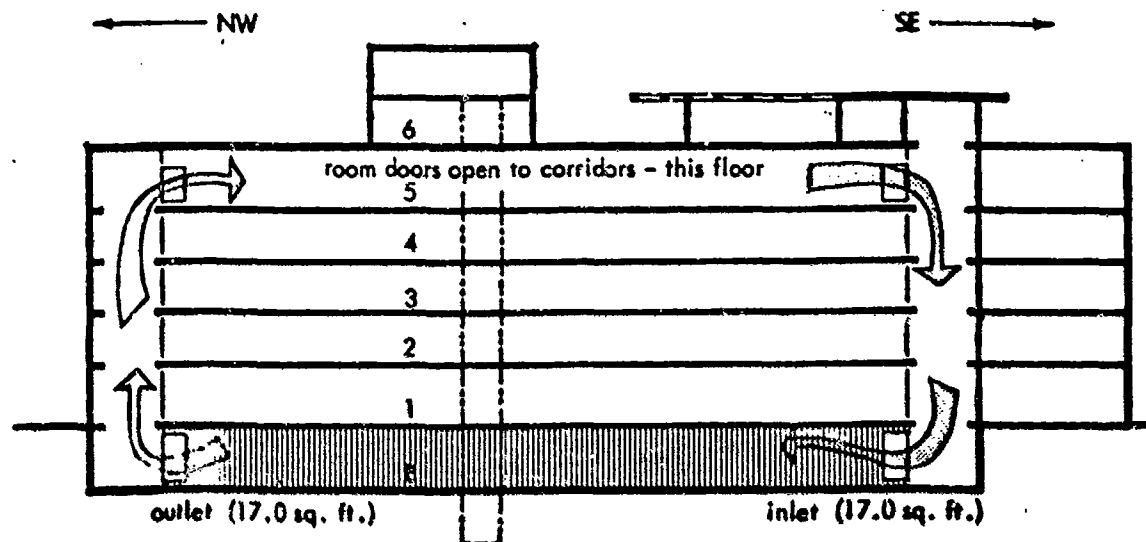
As a result of the decrease in available wall area and reduction in occupancy, the air change rate was lowered slightly from the previous test but the rate of air flow per simulated occupant was again increased. The effective temperature was a rather low 81 F at a 3 ft. height with roughly the same dry bulb temperature in the test space. This would indicate that the increase in available window area and infiltration areas around the windows had the desired effect of reducing the moisture in the air to better proportions.

BUILDING NO. 3

TEST NO. 13

8/7/62 (1200) - 8/8/62 (0800)

75 OCCUPANTS - 20 SQ. FT. / PERSON



OUTSIDE CONDITIONS

air temperature	64 - 88F
relative humidity	50 - 70%
wind	W 7 mph
comments	hot, humid

EFFECTIVE TEMPERATURE (based on full moisture load)

ave. outlet (3' ht.)	81.0F
ave. outlet (5' ht.)	82.0F

DRY BULB TEMPERATURE

ave. inlet (entire door)	78.4F
ave. outlet (entire door)	84.5F
ave. room (5' ht.)	83.3F

RATE OF AIR FLOW

cfm/person	18 to 19
air changes/hour	5.5

WET BULB TEMPERATURE (based on full moisture load)

3' ht. ave. inlet	74.0F
ave. outlet	80.0F
5' ht. ave. inlet	74.0F
ave. outlet	80.5F

COMMENTS

14.7 lb/hr humidity input
(full load).
Equilibrium reached.

Figure 55

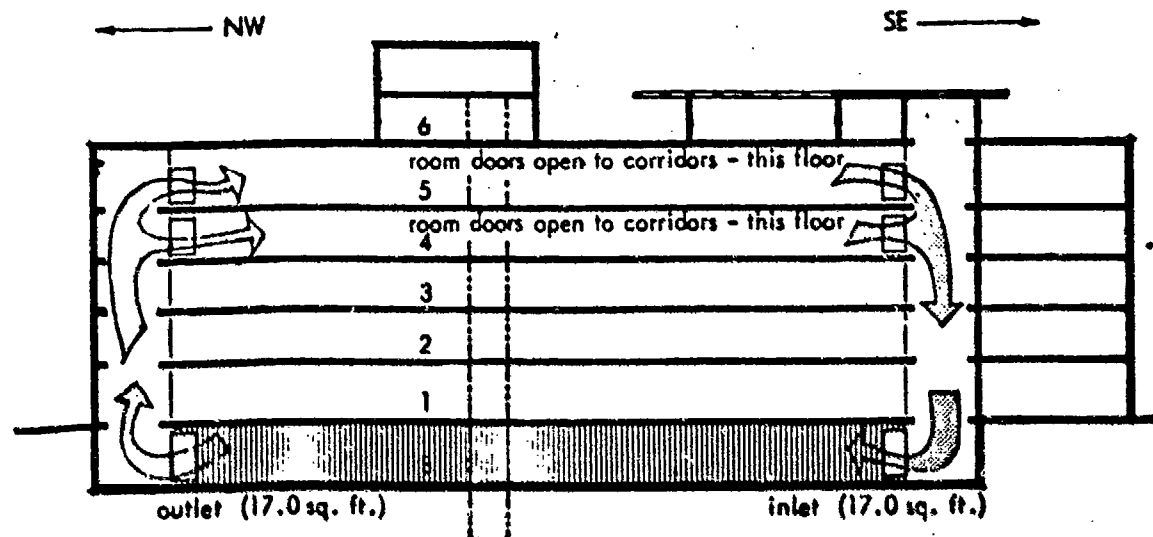
It was shown in Tests #12 and #13 that the opening of the dormitory room doors had a desirable effect on improving conditions in the test spaces. In Test #14 (Figure 56) the simulated occupancy was again raised to the maximum of 150, equivalent to 10 sq. ft. per person. Also, the stair tower doors to the top two floors were now opened and the dormitory room doors on each floor were opened. It was expected that the increased volume and wall area would help dissipate more heat and moisture and in this manner improve conditions in the test space to a tolerable point. However, this did not prove to be the case as the test had to be terminated before equilibrium was reached because of excessive effective temperature in the test space. The ambient outside conditions at the time of this test may very well have caused the poor results since the weather was hot and humid.

BUILDING NO. 3

TEST NO. 14

8/8/62 (1030) - 8/8/62 (2100)

150 OCCUPANTS - 10 SQ. FT. / PERSON



OUTSIDE CONDITIONS

air temperature 55 - 84F
relative humidity 40 - 60%
wind N 2-3 mph
comments hot, clear

EFFECTIVE TEMPERATURE (based on full moisture load)

ave. outlet (3' ht.) 84.0F
ave. outlet (5' ht.) 85.0F

DRY BULB TEMPERATURE

ave. inlet (entire door) 79.8F
ave. outlet (entire door) 86.6F
ave. room (5' ht.) 85.3F

RATE OF AIR FLOW

cfm/person 10 to 12
air changes/hour 6 to 7

WET BULB TEMPERATURE (based on full moisture load)

3' ht. ave. inlet 75.3F
ave. outlet 81.0F
5' ht. ave. inlet 75.3F
ave. outlet 82.3F

COMMENTS

30 lb/hr moisture input
(near full load).
Equilibrium not established.

Figure 56

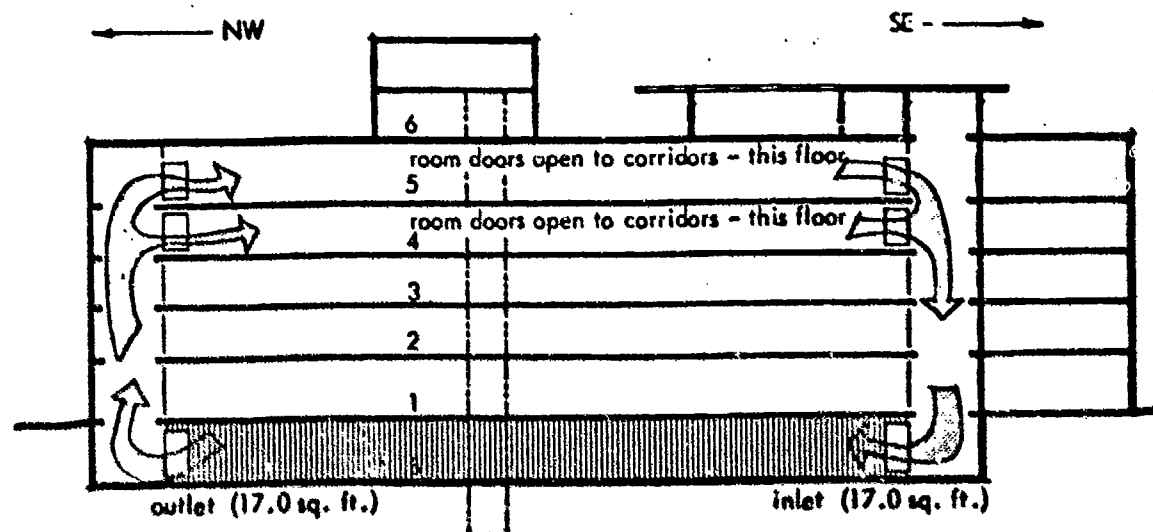
In Test #15 (Figure 57) the simulated occupancy was changed to account for 100 people in an effort to see if the effect of decreasing occupancy would improve conditions. The situation was the same as in Test #14, except for the lower occupancy. The stair tower doors leading into the top two floors were again open, as were the dormitory room doors on both floors. This four day test was the longest continuous test conducted in Building No. 3. The air change rate was about the same as had been found in Test #12 under similar conditions of occupancy, about 5 air changes per hour, even though the window surface area was increased greatly. This might be accounted for by the fact that during this test period the ambient outside conditions were much different than during Test #12. The ambient conditions were cold and damp with a high relative humidity. More condensation would likely occur but the migration of moisture to the outside from the inside would likely be slower. It is also true that the results of Test #12 indicated that for the given sensible and latent load, the test space conditions had been more than adequate. A change for the better then, as in this test, would not be too noticeable.

BUILDING NO. 3

TEST NO. 15

8/9/62 (0830) - 8/13/62 (1600)

100 OCCUPANTS - 15 SQ. FT. / PERSON



OUTSIDE CONDITIONS

air temperature	50 - 80F
relative humidity	40 - 90%
wind	NE 2-5 mph
comments	variable

EFFECTIVE TEMPERATURE (based on full moisture load)

ave. outlet (3' ht.)	81.0F
ave. outlet (5' ht.)	81.0F

DRY BULB TEMPERATURE

ave. inlet (entire door)	77.3F
ave. outlet (entire door)	84.7F
ave. room (5' ht.)	82.3F

RATE OF AIR FLOW

cfm/person	12 to 13
air changes/hour	5

WET BULB TEMPERATURE (based on full moisture load)

3' ht. ave. inlet	68.7F
ave. outlet	77.5F
5' ht. ave. inlet	68.9F
ave. outlet	77.9F

COMMENTS

22 lb/hr moisture input
(full load).
Never at equilibrium.
Room temperature dropping;
outside temperature low.

Figure 57

For Test #16 (Figure 58) the conditions were returned to those of full occupancy or to sensible and latent load of 150 people in a space averaging about 83 F dry bulb temperature. These occupancy conditions were the same as those of Test #11 in which the equilibrium conditions reached were considered to be unsuitable for continued occupancy, and Test #14 where equilibrium conditions had not been reached. The addition of an open window on the top floor of the air flow circuit, along with the additional window space available for cooling and condensation were expected to create an improvement in conditions for this test.

The air change rate in this test proved to be substantially the same as had been found in Test #11, varying between 7 and 9 air changes per hour. During this test, however, the effective temperature remained at or below 83 F whereas previously the effective temperature had been near 85 F. The only apparent reason for this improved condition was the open window on the top floor. The open window was located on the leeward end of the building. This did not create a path for wind to flow through the building as had been done in some of the initial tests. However, it did seem to provide adequate means of dissipating excessive heat and moisture in the circulating air.

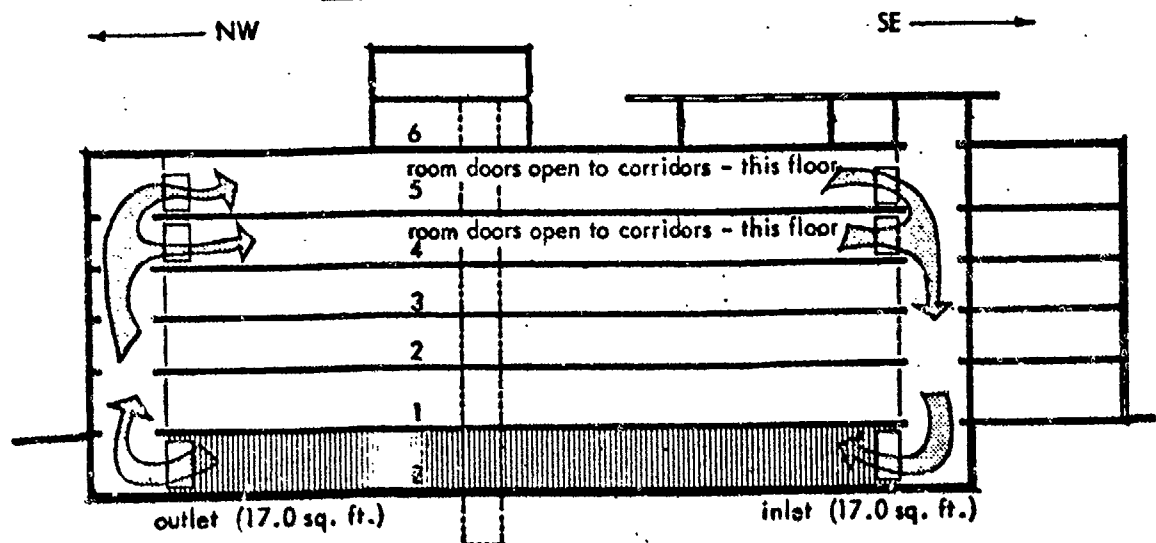
The effects of many variables have been qualitatively deduced from this series of tests, although no quantitative results can be formulated. The qualitative results are discussed in more detail in the Summary and Conclusions of Chapter 7.

BUILDING NO. 3

TEST NO. 16

8/13/62 (1700) - 8/14/62 (0830)

150 OCCUPANTS - 10 SQ. FT. / PERSON



OUTSIDE CONDITIONS

air temperature 60 - 70F
 relative humidity 75 - 90%
 wind S 1-5 mph
 comments mild, humid

EFFECTIVE TEMPERATURE (based on full moisture load)

ave. outlet (3' ht.) 83.0F
 ave. outlet (5' ht.) 83.0F

DRY BULB TEMPERATURE

ave. inlet (entire door) 77.1F
 ave. outlet (entire door) 86.2F
 ave. room (5' ht.) 83.2F

RATE OF AIR FLOW

cfm/person 12 to 15
 air changes/hour 7 to 9

WET BULB TEMPERATURE

3' ht. ave. inlet 71.5F
 ave. outlet 80.2F
 5' ht. ave. inlet 71.5F
 ave. outlet 80.3F

COMMENTS

28 lb/hr moisture input
 (somewhat less than full load).
 Equilibrium established.

Figure 5B

One additional test, Test #17 (Figure 59), was made at this time. In this test, an attempt was made to ascertain the conditions in a "side room" under simulated conditions similar to those of Test #16 except that no deliberate openings appeared in the air flow circuit. The location and configuration of the "side room" in relation to the main test space is shown on the basement plan (Figure 42).

Interest was expressed as to what conditions would exist if "side rooms" were opened into the main basement test space. These "side room" spaces could not be expected to exhibit the air change rate found in the main test space, primarily because they would not have separate inlet and outlet. The fact that there is only one opening to the "side room" means that air movement in and out of the room would have to take place through the same opening. Since this is the case, the water vapor method of determining the air change rate becomes practically impossible in the "side room" itself. Therefore, the tracer gas decay method of determining air change rate was used in the "side room" and the air change rate did not exceed the limits of capability of the method.

The main test space was considered to contain 150 people or 10 sq. ft. per person, and in the specified "side room" 50 people or 20 sq. ft. per person were simulated. The ratio of sensible to latent heat was not to be different in the spaces, as the "side room" was expected to reach as high a temperature as that in the main test space.

BUILDING NO. 3

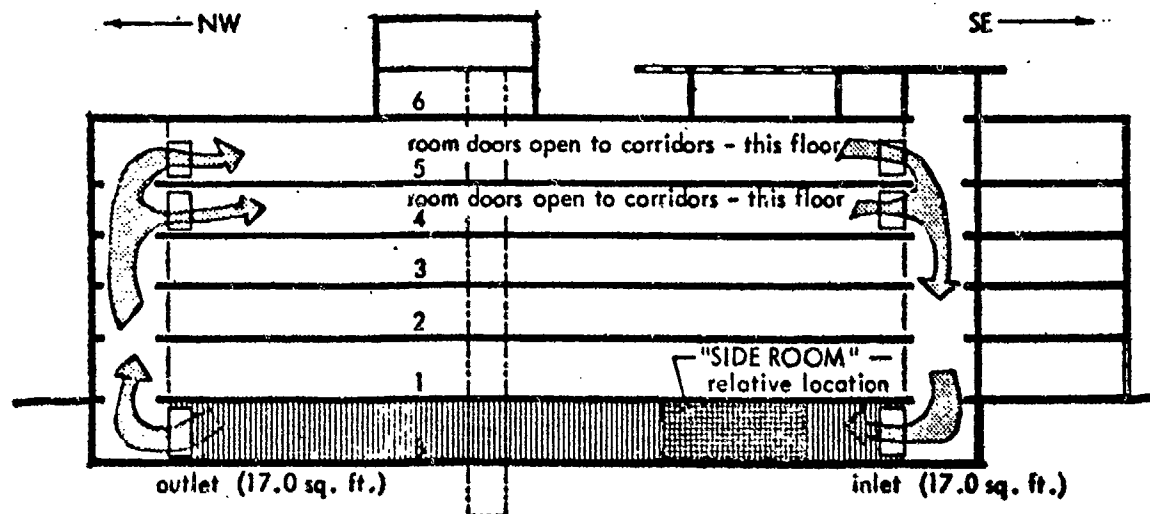
TEST NO. 17

8/17/62 (1000) - 8/17/62 (2000)

MAIN SPACE 150 OCCUPANTS - 10 SQ. FT. / PERSON

"SIDE ROOM" 50 OCCUPANTS - 20 SQ. FT. / PERSON

Data below based on both spaces being occupied



OUTSIDE CONDITIONS

air temperature 68 - 75F
 relative humidity 45 - 50%
 wind SW 4-8 mph
 comments clear, cool

EFFECTIVE TEMPERATURE (based on full moisture load)

ave. outlet (3' ht.) 82.0F
 ave. outlet (5' ht.) 82.5F
 ave. "side room" (5' ht.) 81.5F

DRY BULB TEMPERATURE

ave. inlet (entire door) 77.0F
 ave. outlet (entire door) 85.0F
 ave. room (5' ht.) 83.0F

RATE OF AIR FLOW (both spaces)

cfm/person (200 occ.) 8 to 10
 air changes/hr. " 6 to 8

WET BULB TEMPERATURE (based on full moisture load)

3' ht. ave. inlet 75.0F
 ave. outlet 80.5F
 5' ht. ave. inlet 75.0F
 ave. outlet 81.0F

RATE OF AIR FLOW ("side room" only)

cfm/person (50 occ.) 8 to 9
 air changes/hr. " 2.5 to 3

COMMENTS

All data pertains to main test space,
 unless otherwise noted.
 44+ lb/hr humidity input (full load -
 both spaces).
 Equilibrium reached.
 Condensation on "side room" wall.

Figure 59

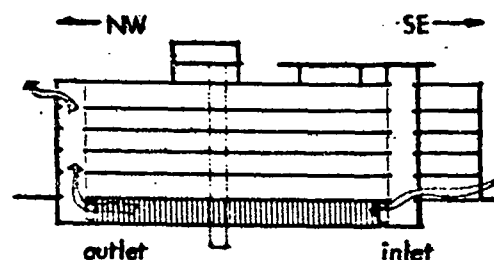
It was anticipated that the water vapor method of determining air change rate could be used in the total basement space, giving at least an average air change rate for the two combined spaces. It was found, however, that some condensation on the cold exterior wall in the "side room" took place throughout the testing. The amount of condensation did not seem to be enough to radically change the calculated air change rate, although that rate would no doubt be lower had no condensation taken place. The calculated air change rate was between 6 and 8 air changes per hour in the two combined spaces. Due to the condensation, these could probably be more accurately placed between 5 and 8 air changes per hour.

The results of the tracer gas decay method, utilizing the N.B.S. Portable Infiltration Meter, indicated an air change rate in the "side room" which was higher than had been anticipated and was on the borderline of the range of reliability of the instrument. With a double door opening of 34.8 sq. ft. into the "side room" an air change rate of 3 air changes per hour was found. Later, with a single door opening of 17.4 sq. ft. into the "side room" an air change rate of 2.5 air changes per hour was obtained.

The temperature in both main test space and "side room" rose above 80 F, but the average effective temperature in the main test space was never above 82 F and the effective temperature in the "side room" did not reach even this point. This is in line with the results in the previous test.

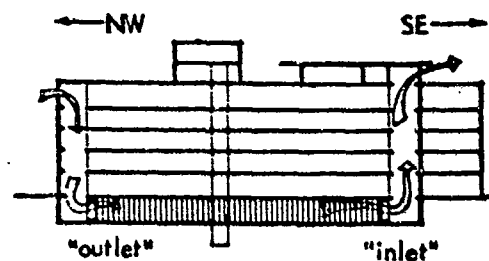
One fact that must not be ignored is that the "side room" opening was near the inlet to the main test space, and as a result, the air flowing past the door into the "side room" was the cool inlet air. There is no doubt that this situation helped to hold the "side room" temperature and humidity to comfortable conditions, as well as to improve the air change rate in the room. Had the "side room" been off the warm or outlet end of the main test space, the air that would be changing would already be hot and humid. Then, the temperature in the "side room" would necessarily have risen above the temperature in the main test space. The air change rate would probably have been lower, and this also would have tended to increase the "side room" temperature. The "side room" effective temperature, under these conditions, may have approached the maximum limit or surpassed it.

A summary of pertinent test data for Building No. 3 is shown in Table 7. The various air flow circuit configurations employed in the tests are also presented (Figure 60).



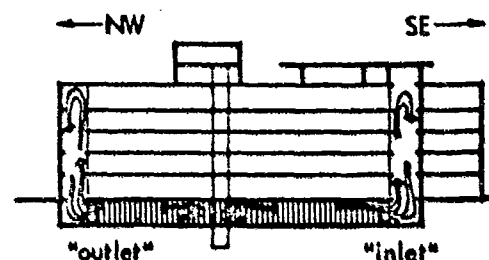
TEST NO. 1

Windows at base of SE stair tower open.
 Windows at top of NW stair tower open.
 Vol. ratio — test space to circulation space = 0.95.
 Inlet opening 17.0 sq. ft.
 Outlet opening 17.0 sq. ft.



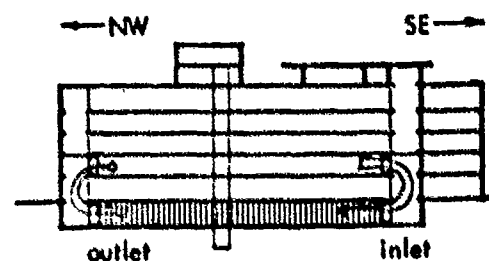
TEST NO. 4

Deliberate openings at top of both stair towers.
 Mechanical ventilation system operating.
 Vol. ratio — test space to circulation space = 0.95.
 "Inlet" opening 17.0 sq. ft.
 "Outlet" opening 17.0 sq. ft.



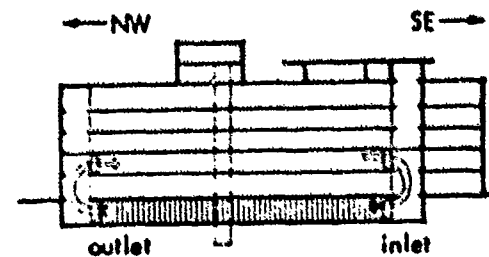
TEST NO. 6

No deliberate openings except basement doors to stair towers.
 Vol. ratio — test space to circulation space = 0.95.
 "Inlet" opening 17.0 sq. ft.
 "Outlet" opening 17.0 sq. ft.



TEST NO. 7

Stair tower closures above second story.
 Stair tower doors open on second story.
 Vol. ratio — test space to circulation space = 0.60.
 Inlet opening 17.0 sq. ft.
 Outlet opening 17.0 sq. ft.



TEST NO. 9

Stair tower closures above second story.
 Stair tower doors open on second story.
 Vol. ratio — test space to circulation space = 0.60.
 Inlet opening 17.0 sq. ft.
 Outlet opening 17.0 sq. ft.

COMPARISON OF AIR FLOW CIRCUIT CONFIGURATIONS - BUILDING NO. 3

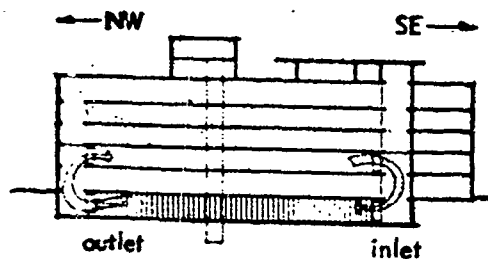
Figure 60

Table 7

TEST SUMMARY BUILDING NO. 3

TEST NO.	1	4	6	7	9
Duration of test	33 hrs.	26 hrs.	27 hrs.	68 hrs.	16 hrs.
Simulated occupancy	none	none	150	150	150
Floor area per person	*	*	10 sq. ft.	10 sq. ft.	10 sq. ft.
Outside conditions					
air temperature	66-82F	61-78F	50-69F	60-81F	60-78F
relative humidity	50-90%	70-95%	45-85%	30-80%	50-80%
wind direction	S	NW	SW	S	W
wind speed	3-5 mph	7 mph	2-4 mph	3-5 mph	3 mph
comments	cloudy, humid	showers	cloudy, cool	warm, sunny	clear, hot
Dry bulb temperature					
ave. inlet	70.0F	70.5F	77.0F	74.0F	76.5F
ave. outlet	71.0F	67.0F	79.0F	81.0F	85.9F
ave. room	73.2F	72.5F	83.6F	81.6F	83.9F
Wet bulb temperature					
ave. inlet (3')	*	*	62.5F	63.8F	71.5F
ave. outlet (3')	*	*	76.0F	78.5F	81.0F
ave. inlet (5')	*	*	64.5F	63.8F	71.5F
ave. outlet (5')	*	*	82.0F	79.2F	82.5F
Effective temperature					
ave. outlet (3')	*	*	76.0F sat.	81.0F	83.0F
ave. outlet (5')	*	*	82.0F sat.	81.5F	84.5F
Air flow					
cfm/person	*	*	2	5 to 7	8
air changes/hour	Rapid.	Rapid.	1 to 1.5	3 to 4	4.5 to 5
Comments	Deliberate openings. *No occupants.	Deliberate openings. *No occupants.	Token moisture load. Equilibrium reached.	Token moisture load. Equilibrium reached.	Partial moisture load. Equilibrium reached.

Water vapor method for determining air change rates used in all tests except Test #17.



TEST NO. 10

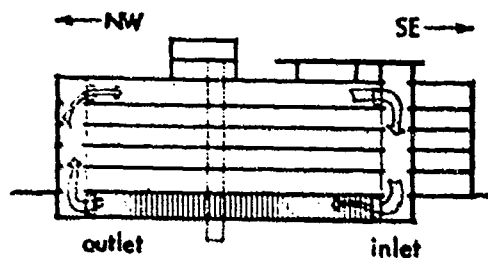
Stair tower closures above second story.

Stair tower doors open on second story.

Vol. ratio — test space to circulation space = 0.60.

Inlet opening 17.0 sq. ft.

Outlet opening 17.0 sq. ft.



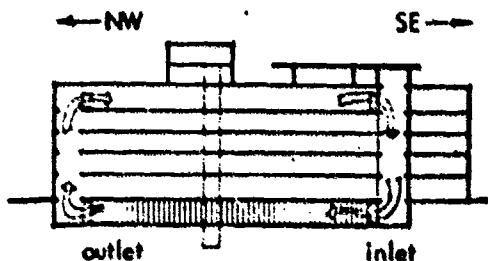
TEST NO. 11

Stair tower doors open on fifth story.

Vol. ratio — test space to circulation space = 0.45.

Inlet opening 17.0 sq. ft.

Outlet opening 17.0 sq. ft.



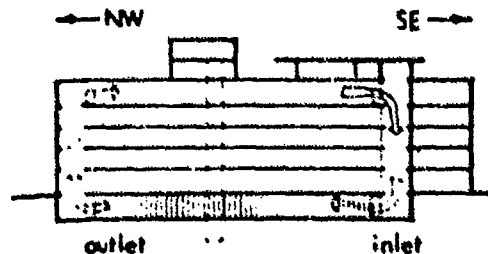
TEST NO. 12

Stair tower doors open on fifth story.

Vol. ratio — test space to circulation space = 0.45.

Inlet opening 17.0 sq. ft.

Outlet opening 17.0 sq. ft.



TEST NO. 13

Stair tower doors open on fifth story.

Room doors on fifth story open to corridors.

Vol. ratio — test space to circulation space = 0.20.

Inlet opening 17.0 sq. ft.

Outlet opening 17.0 sq. ft.

COMPARISON OF AIR FLOW CIRCUIT CONFIGURATIONS - BUILDING NO. 3

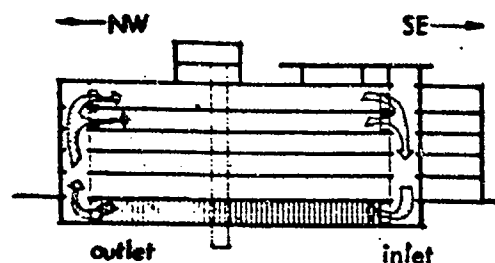
Figure 60 (Cont.)

Table 7 (Cont.)

TEST SUMMARY BUILDING NO. 3

TEST NO.	10	11	12	13
Duration of test	13 hrs.	30 hrs.	8 hrs.	20 hrs.
Simulated occupancy	150	150	100	75
Floor area per person	10 sq. ft.	10 sq. ft.	15 sq. ft.	20 sq. ft.
Outside conditions				
air temperature	68-80F	67-80F	72-92F	64-88F
relative humidity	30-46%	40-74%	40-80%	50-70%
wind direction	NW	S	S	W
wind speed	3 mph	2-5 mph	6 mph	7 mph
comments	clear, hot	clear, hot	hot	hot, humid
Dry bulb temperature				
ave. inlet	77.2F	77.7F	77.8F	78.4F
ave. outlet	86.4F	86.4F	84.1F	84.5F
ave. room	84.8F	84.5F	83.2F	83.5F
Wet bulb temperature				
ave. inlet (3')	77.5F	74.0F	74.0F	74.0F
ave. outlet (3')	83.0F	81.0F	80.0F	80.0F
ave. inlet (5')	78.0F	74.0F	74.2F	74.0F
ave. outlet (5')	84.0F	83.0F	82.0F	80.5F
Effective temperature				
ave. outlet (3')	84.0F	83.0F	82.0F	81.0F -
ave. outlet (5')	84.5F	84.5F	82.8F	82.0F
Air flow				
cfm/person	10 to 12	12 to 15	13 to 15	18 to 19
air changes/hour	6 to 7	7 to 9	5 to 6	5.5
Comments	Full mois- ture load. Equilibrium not reached.	Full mois- ture load. Equilibrium reached.	Full mois- ture load. Equilibrium reached.	Full mois- ture load. Equilibrium reached.

Water vapor method for determining air change rates used in all tests except Test #17.



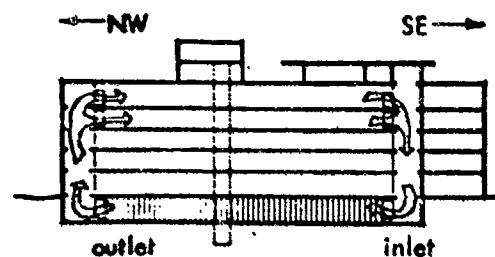
TEST NO. 14

Stair tower doors open on fourth and fifth stories.
Room doors on fourth and fifth stories open to corridors.

Vol. ratio — test space to circulation space = 0.10.

Inlet opening 17.0 sq. ft.

Outlet opening 17.0 sq. ft.



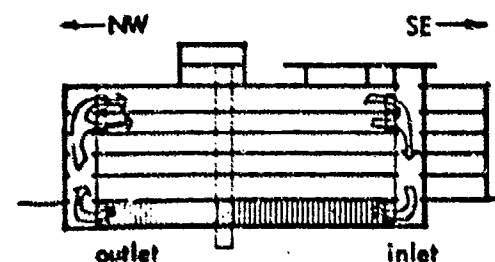
TEST NO. 15

Stair tower doors open on fourth and fifth stories.
Room doors on fourth and fifth stories open to corridors.

Vol. ratio — test space to circulation space = 0.10.

Inlet opening 17.0 sq. ft.

Outlet opening 17.0 sq. ft.



TEST NO. 16

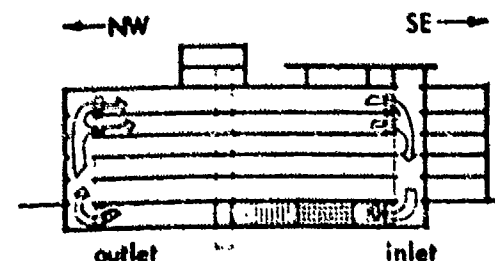
Stair tower doors open on fourth and fifth stories.
Room doors on fourth and fifth stories open to corridors.

One window open on fourth story at NW end.

Vol. ratio — test space to circulation space = 0.10.

Inlet opening 17.0 sq. ft.

Outlet opening 17.0 sq. ft.



TEST NO. 17

Building configuration same as in Test 15 with the addition of a "side room" in the circuit.

Vol. ratio — "side room" to main test space = 0.70.

"Side room" opening 17.4 sq. ft. — single door.

34.8 sq. ft. — double doors.

COMPARISON OF AIR FLOW CIRCUIT CONFIGURATIONS - BUILDING NO. 3

Figure 60 (Cont.)

Table 7 (Cont.)

TEST SUMMARY BUILDING NO. 3

TEST NO.	14	15	16	17
Duration of test	11 hr.	104 hrs.	16 hrs.	10 hrs.
Simulated occupancy	150	100	150	150+50*
Floor area per person	10 sq. ft.	15 sq. ft.	10 sq. ft.	10+20*sq.ft.
Outside conditions				
air temperature	55-84F	50-80F	60-70F	68-75F
relative humidity	40-60%	40-90%	75-90%	45-50%
wind direction	N	NE	S	SW
wind speed	2-3 mph	2-5 mph	1-5 mph	4-8 mph
comments	hot, clear	variable	mild, humid	clear, cool
Dry bulb temperature				
ave. inlet	79.0F	77.3F	77.1F	77.0F
ave. outlet	86.6F	84.7F	86.2F	85.0F
ave. room	85.3F	82.3F	83.2F	83.0F
Wet bulb temperature				
ave. inlet (3')	75.3F	68.7F	71.5F	75.0F
ave. outlet (3')	81.0F	77.5F	80.2F	80.5F
ave. inlet (5')	75.3F	68.9F	71.5F	75.0F
ave. outlet (5')	82.3F	77.9F	80.3F	81.0F
Effective temperature				
ave. outlet (3')	84.0F	81.0F	83.0F	82.0F
ave. outlet (5')	85.0F	81.0F	83.0F	82.5F
ave. "side room" (5')				81.5F*
Air flow				
cfm/person	10 to 12	12 to 13	12 to 15	8 to 9*
air changes/hour	6 to 7	5	7 to 9	2.5 to 3*
Comments	Full mois- ture load. Equilibrium <u>not</u> reached.	Full mois- ture load. Equilibrium <u>not</u> reached.	Full mois- ture load. Equilibrium reached.	Full mois- ture load. Equilibrium reached. **side room*
Water vapor method for determining air change rates used in all tests except Test #17.				

CHAPTER 6

EXPERIMENTAL VENTILATION FACILITY

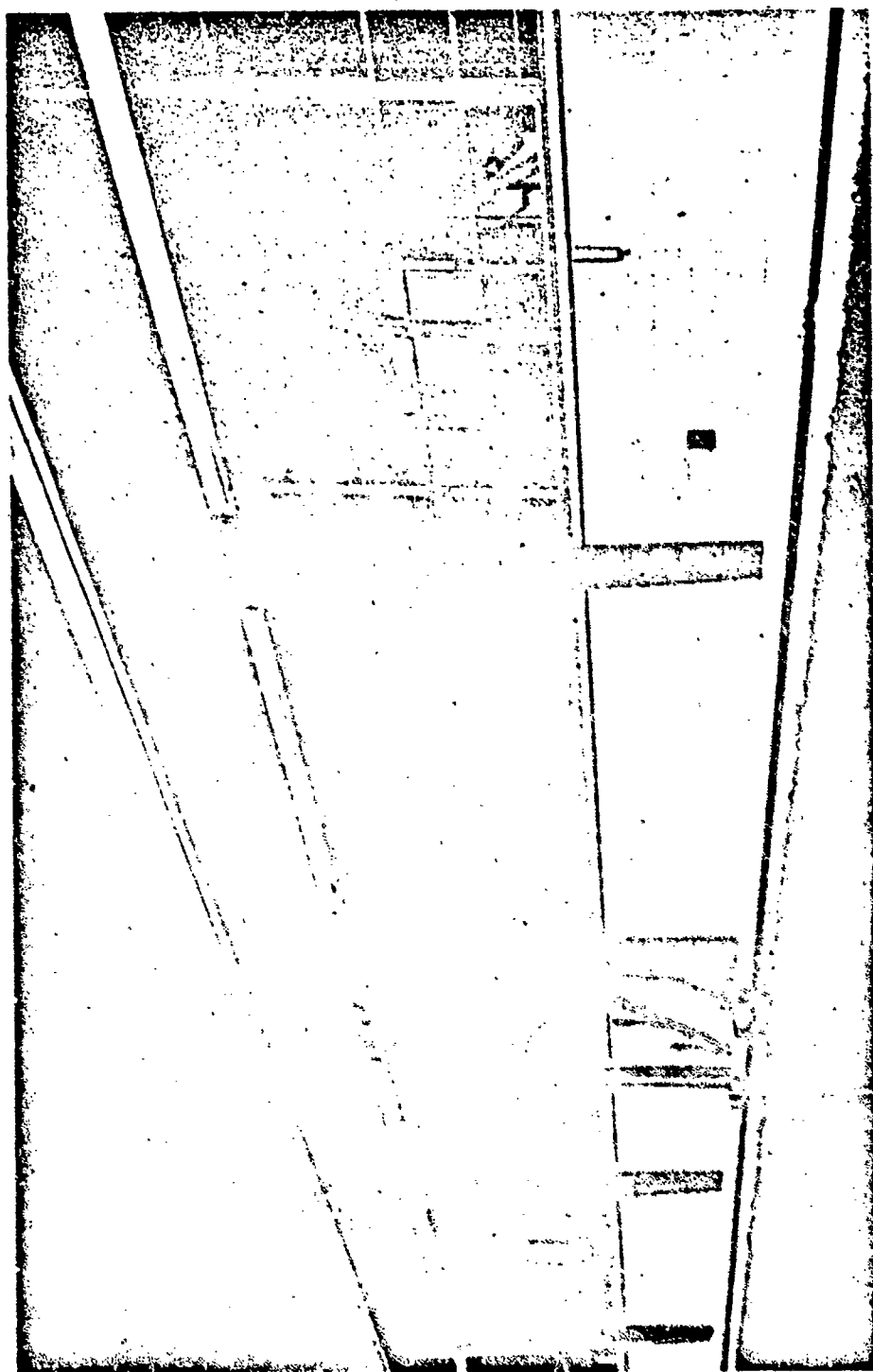
PURPOSE OF FACILITY

One of the main objectives of this research project was the development of a reliable method for measuring the rate of natural ventilation in shelter spaces. Because of the difficulty encountered in testing the reliability of various methods under uncontrolled conditions in potential shelter spaces, a temporary facility was constructed in an existing research building for this purpose. The facility was to be used as a means of checking different equipment and methods under various known conditions of air change rate, temperature, and humidity in the test chamber. The control of these conditions could be assured only with the use of a facility designed for this purpose.

DESCRIPTION OF FACILITY

Space in which to erect a test facility was obtained in a newly developed research center. The butler frame building (Figure 61) has tectum roof decking and continuous windows run from a 4 ft. height to the top of the 10'-8" high brick wall. Interior partitions eight feet high are the movable metal type with plywood panels. All necessary mechanical and electrical facilities are within easy access.

The partition between two 30' x 30' rooms was removed to provide a space approximately 30' x 60'. The entire space was sealed from adjacent rooms



EXTERIOR VIEW — RESEARCH BUILDING

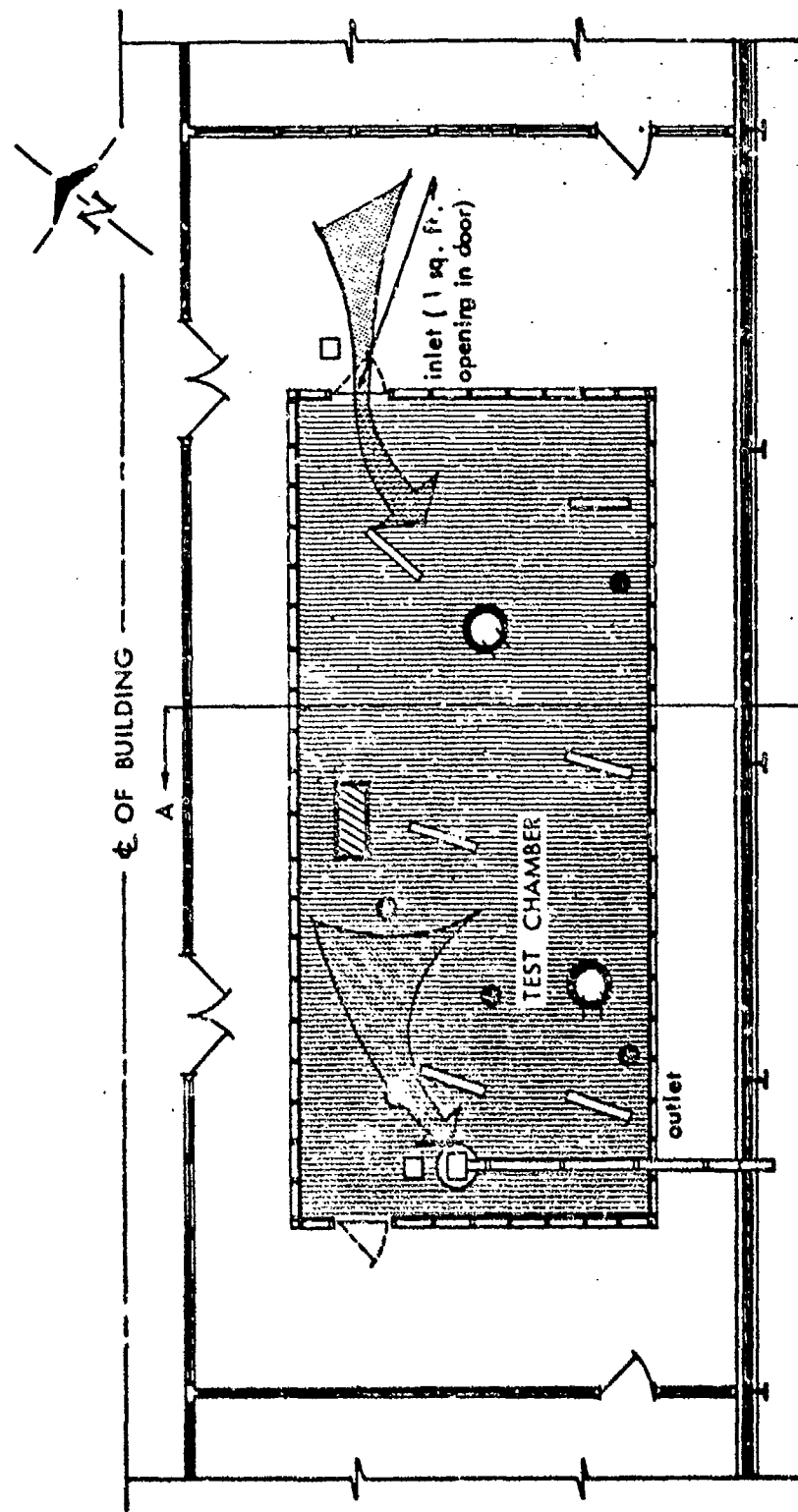
Figure 61

as tightly as possible without taping. Plywood panels were installed above the partitions to accomplish this closure.

A plan, section, and exterior view of the test chamber which was constructed within the 30' x 60' space are illustrated (Figures 62, 63, and 64). The chamber was designed to satisfy several criteria. Since air change rates had to be determined as accurately as possible, the test chamber was completely sealed with caulking and tape. To prevent the introduced moisture from escaping, stud walls and wood joist ceiling were covered inside with foil-backed gypsum board with the foil facing inward. To reduce the effects of solar radiation through the windows in the building wall, a foil-backed gypsum board was also installed on the outside of the studs with foil facing south. These panels are visible in the exterior photo of the building (Figure 61).

The approximate size of the test chamber was 20' x 40' x 8'. Water supply, power supply, illumination, and drainage facilities were provided within the space. Lamps outside the test chamber which were not absolutely necessary for illumination were dismantled to reduce extraneous heat loads. One door was provided at each end of the facility.

The inlet area to the test chamber (Figure 64) was a one square foot clear area cut in the inlet door. This small area provided the means for obtaining a very accurate indication of inlet air wet and dry bulb temperatures. These were measured with a portable, automatic psychrometer described in

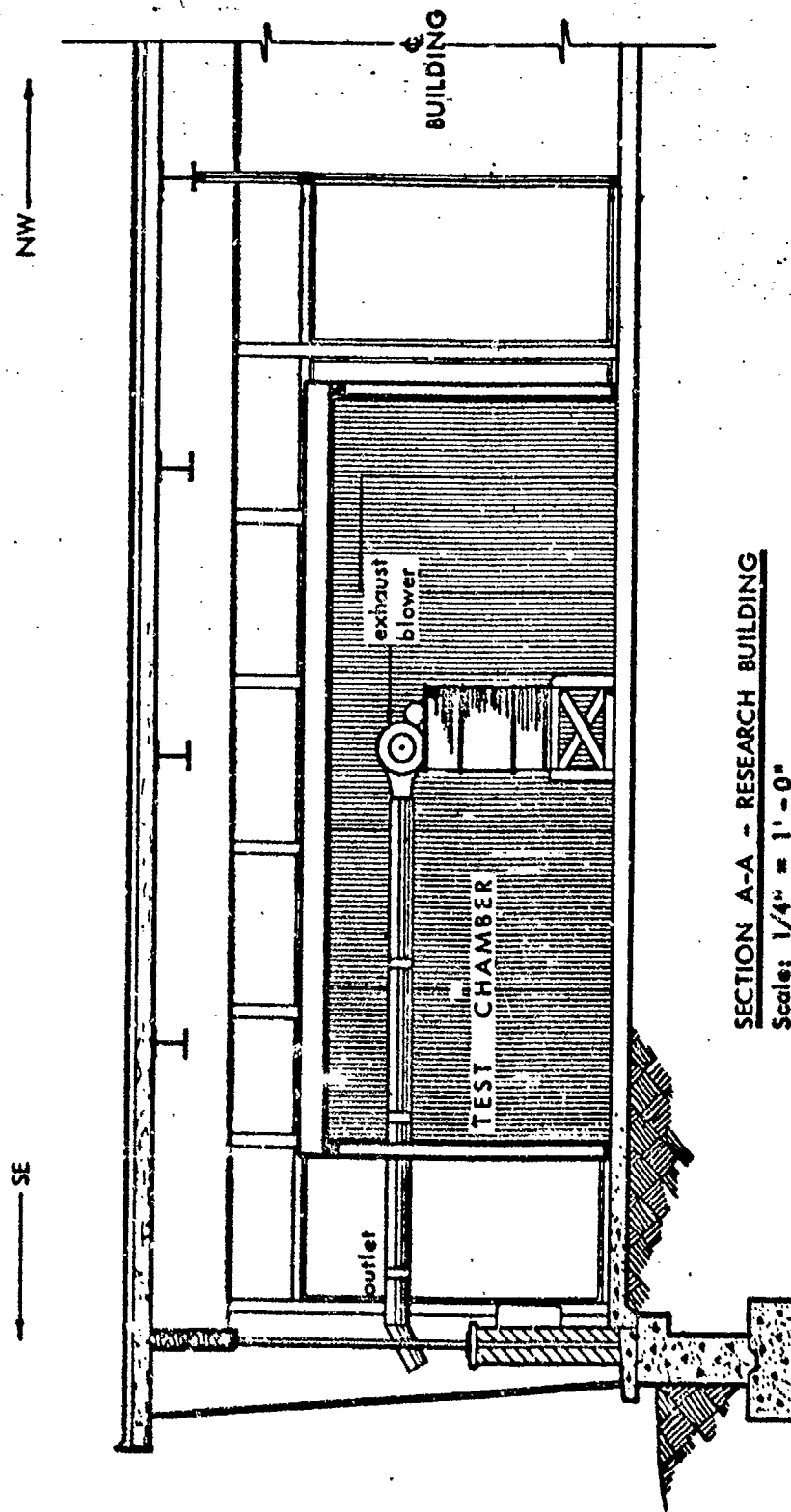


- LEGEND:**
- tracer sensing device
 - lamp bank
 - humidifier barrel
 - automatic psychrometer
 - ▨ control panel station
 - ⊞ exhaust blower

FLOOR PLAN SHOWING TEST CHAMBER

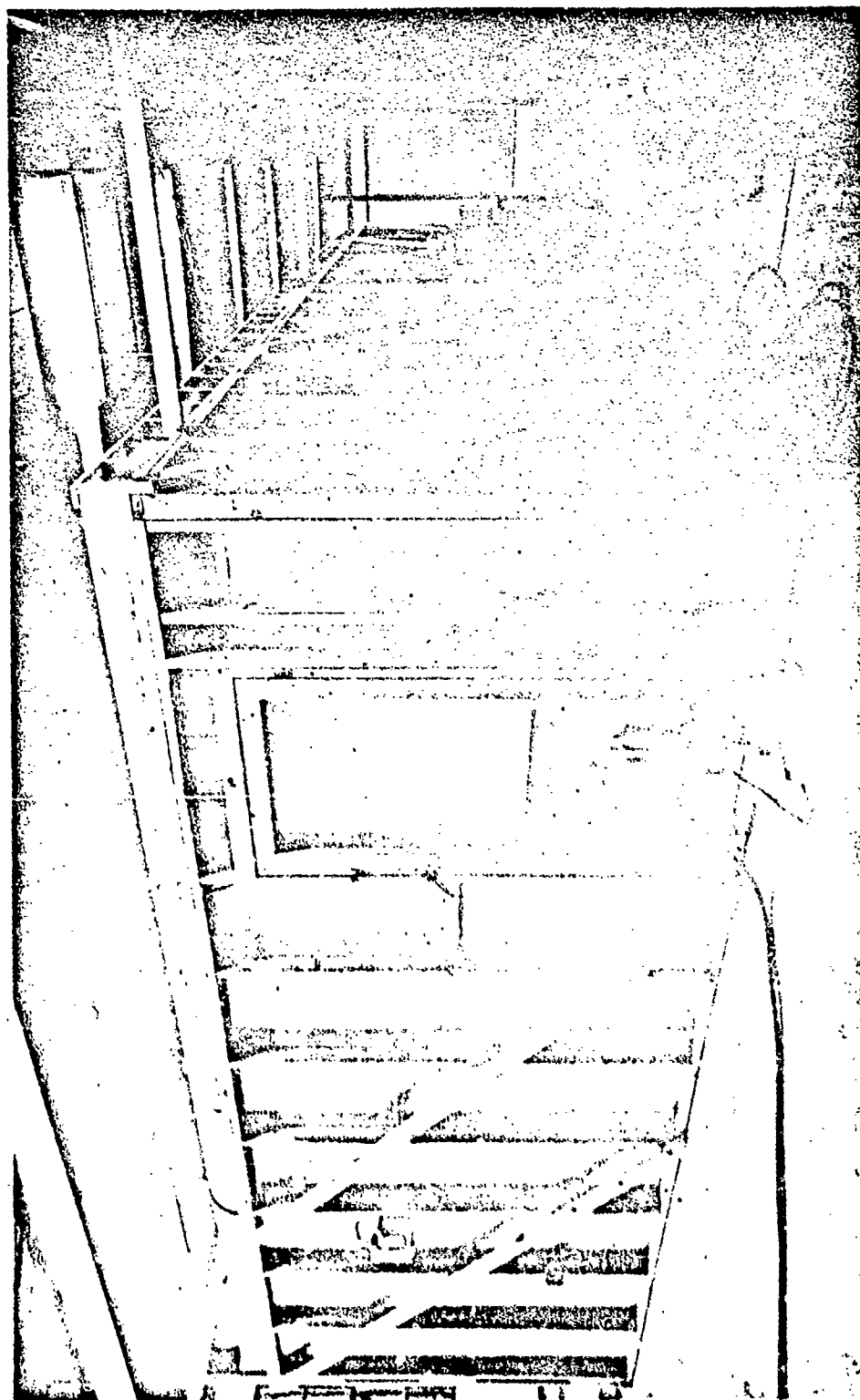
Scale: 1/8" = 1' - 0"

Figure 62



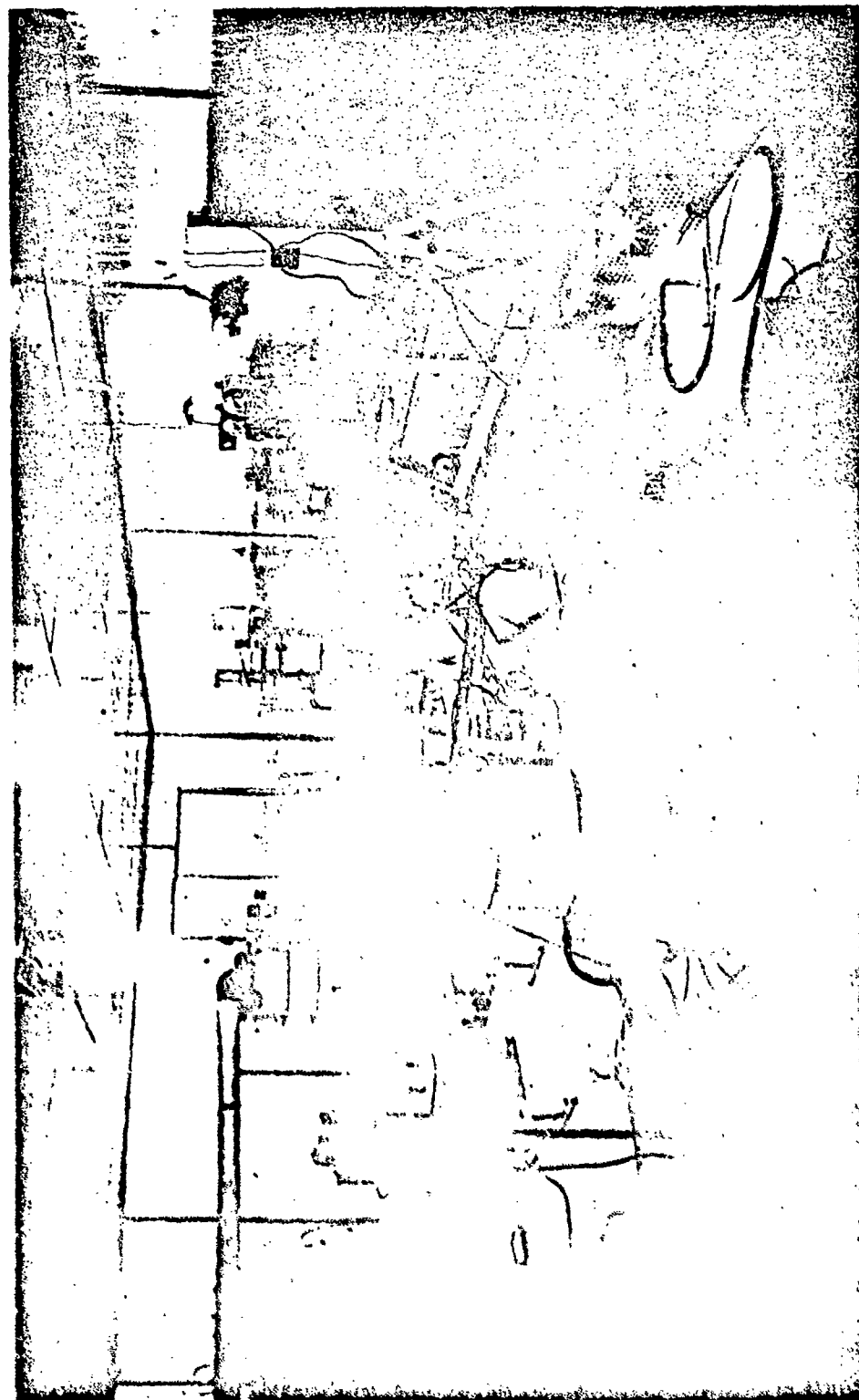
SECTION A-A - RESEARCH BUILDING
Scale: 1/4" = 1'-0"

Figure 63



EXTERIOR VIEW OF TEST CHAMBER

Figure 64



INTERIOR VIEW OF TEST CHAMBER

Figure 65

Chapter 2. The air was moved through the test chamber by means of a 500 cfm centrifugal exhaust blower, which could be modulated to provide a range of air flow. The outlet conditions were measured at the entrance to the exhaust blower. The air was exhausted from the test chamber to the atmosphere through an 8" diameter galvanized pipe, which extended through the chamber wall to the exterior of the building. The exhaust blower along with other equipment located within the test chamber is illustrated in an interior view (Figure 65).

TEST RESULTS

Table 8 shows the results of a series of tests which were conducted in the test chamber for comparison of water vapor and tracer gas decay methods of determining air change rates. Helium was the tracer gas used in conjunction with the Portable Infiltration Meter described in Chapter 2.

No attempt was made to simulate a specific number of occupants in the test chamber by supplying a certain ratio of sensible to latent heat. Therefore, no effective temperatures have been tabulated. The exhaust blower provided control of the air change rate which was kept constant during each test. The air change rates indicated by the water vapor method and tracer gas decay method are tabulated for comparison to this known rate. Space conditions were allowed to stabilize during a 12 to 24 hour period prior to testing.

The tracer gas decay method appears to give a fair degree of accuracy for air change rates at or below 3 air changes per hour. For higher rates, however, the results are less reliable.

Table 8
COMPARISON OF AIR CHANGE RATES BY WATER VAPOR AND
TRACER GAS DECAY METHODS

TEST NO.	1	2	3	4	5	6	7	8	9	10	11	12	13
Dry bulb temp.													
ave. inlet	84.5	77.0	84.0	83.0	75.0	78.5	75.0	69.0	68.5	66.0	72.5	71.0	76.5
ave. outlet	92.0	87.0	89.0	87.5	86.0	86.0	84.5	79.5	78.0	78.0	82.5	85.0	84.0
Wet bulb temp.													
ave. inlet	66.0	65.0	69.0	62.0	57.0	58.5	58.0	53.0	52.0	49.0	56.5	56.0	58.5
ave. outlet	84.0	77.5	79.0	64.5	73.0	74.0	74.0	64.5	60.5	60.5	67.0	73.0	68.0
Water added, lbs/hr	16.0	10.0	10.8	0.0	10.0	9.0	20.0	9.5	5.8	5.7	5.2	9.2	5.6
Air flow, air changes/hr													
known	2.7	2.7	2.75	2.75	2.25	2.25	4.6	4.6	4.7	3.25	2.4	2.5	2.6
water vapor method	2.6 to 3.1	2.7 to 3.0	3.1 to 3.3	*	2.3 to 2.5	2.3 to 2.5	4.2 to 4.8	4.7	4.3 to 5.1	3.4 to 4.0	2.5 to 2.7	2.6 to 2.7	2.8 to 2.9
tracer gas de- cay method	2.5 to 3.2	2.6 to 3.0	2.5 to 2.9	2.9 to 3.2	2.1 to 2.5	2.5 to 3.0	3.8 to 4.3	3.7 to 3.8	3.6 to 4.4	**	**	**	**

** Instrument could not be balanced, possibly due to effects resulting from high humidity of previous tests.
* No moisture added.

It was noted during this series of tests that the dependability of the tracer gas decay method is not limited only by the air change rate. Reliable sensing devices placed at different locations in the space often indicate very different air change rates. It is difficult to determine where these sensing devices should be placed to give an average air change rate through the space. Sensing devices in some locations will indicate very high air change rates while in other locations low rates will be observed. The problem then is to determine what the average air change rate is. Thus, the tracer gas decay method is good for determining air change rates of low magnitude only in the immediate vicinity of the sensing device and cannot be used to determine average air change rates in a large space without considerable difficulty.

The water vapor method seems to be reliable for a large range of air change rates and for different rates of moisture input to the space. Since inlet and outlet conditions are measured automatically throughout the testing period, the water vapor method gives a continuous record of air change rates throughout the test period, and is not restricted, as are tracer gas decay methods, to one or two checks per day. Also, the tracer gas decay method requires continuous attendance of personnel familiar with the instruments being used, but the water vapor method places little additional work load on the part of research personnel. However, in order to obtain useful test results in a potential shelter space using the water vapor method, the full moisture load equal to that which would actually be emitted by the

shelter occupants must be added to the space.

Next to possible moisture condensation on cold surfaces, the greatest concern with the water vapor method is the possible migration of water vapor into or out of the walls, furnishings and other surfaces which would give an untrue record of the air change rate. However, by exercising sufficient care in testing, and by using records obtained only when an equilibrium state has been reached, the results will be as good as any that are obtained by other methods. In future testing it would seem wise to pre-condition the surfaces so that water vapor migration would be minimized. Under this condition, the water vapor method would be the best choice of all presently known methods which could be used.

Another instrument utilizing the tracer gas decay method was tested, with Freon 12 as the tracer. The Westinghouse Electronegative Gas Detector described in Chapter 2 was available for testing in the test chamber for a short period of time, during which favorable results were obtained. However, it was not checked under different conditions of humidity, temperature, and air flow because of time limitations. Therefore, its adaptability to the desired use is not definitely known. From the limited amount of operation in the test chamber, this device seems to have good possibilities. It is easy to operate, and is considered quite stable. However, before it can be recommended for the intended purpose of this research project, it should be more thoroughly checked.

CHAPTER 7

SUMMARY AND CONCLUSIONS

INSTRUMENTATION

An important objective of this research project was to develop reliable techniques for measuring the natural flow of air in shelter spaces. The following are summary statements regarding the applicability of the various methods investigated.

1. Leak detectors, such as the General Electric Type H-1, designed for detecting leaks in refrigeration equipment; are not recommended for measuring air change rates in building spaces.
2. The N.B.S. Portable Infiltration Meter, using helium as the tracer gas, would be satisfactory for determining the air change rate in a building space under certain limiting conditions. These conditions are: (a) a fairly constant temperature and relative humidity; (b) good mixing of the building space air with very little turbulence; and (c) a constant air change rate which is within the limits of the tracer gas decay method and equipment capability (approximately 3 air changes per hour maximum).
3. The Westinghouse Electronegative Gas Detector would be satisfactory for determining the air change rate in a building space under certain limiting conditions. These conditions are: (a) thorough mixing of the

air and the tracer gas in the space; (b) provision of a method of standardization; and (c) a constant air change rate which is within the limits of the tracer gas decay method and equipment capability (approximately 3 to 4 air changes per hour maximum).

4. The tracer gas decay technique, although extremely useful in this work, is not really suited for measuring large quantities of air circulation because of the reasons mentioned in the preceding statements.
5. Direct velocity measurements with a calibrated hot wire anemometer could be used to determine air change rates in building spaces based upon limited observations in this research project. The anemometer must be accurate over the range of velocities that could be expected in this type of study. Air flow must be unidirectional at all inlets and outlets of the space.
6. The water vapor method is the best of the methods used in this study for determining air change rates in building spaces. It is fairly accurate for a large range of air change rates provided a state of moisture stability exists in reference to the surfaces and materials within the space.
7. Comparison of air change rates determined by water vapor and tracer gas decay methods yielded correlations on the order of 1.0 to 1.15 with the known air change rates when equilibrium conditions were

obtained in the test chamber of the experimental ventilation facility.

For air change rates higher than 3 per hour, the tracer gas decay method became less accurate.

TEST PROCEDURE

The following test procedure was developed as a result of the testing programs in this research project.

1. The test space is tightly sealed from adjacent spaces, using tape to close all cracks, except where air is expected to enter and leave the space.
2. Heat and moisture producing equipment is installed in the test space to simulate occupants. Sensing devices are located throughout the space to monitor increases in temperature and humidity.
3. After the temperature and humidity conditions approach equilibrium, the effective temperature can be calculated. This value will normally be maximum at the outlet.
4. The air change rate can be calculated by any reliable method.
5. If the effective temperature exceeds 85 F at any point in the test space, or the air change rate produces less than 3 cfm per person, the space conditions are considered substandard in accordance with criteria for this project.

6. If space conditions are substandard, an attempt should be made to improve them. This improvement might include changing the simulated occupancy and/or changing the air flow circuit.

TEST RESULTS

The following conclusions and statements have been developed based upon data obtained during the testing programs. The conclusions are conservatively stated since many of the variable factors could not be stabilized over a lengthy testing period. Effective temperature has been corrected to full moisture load conditions for those tests in which a reduced moisture load was simulated.

1. Limited time and the priority of other objectives made it impractical to determine what percentage of fresh outdoor air was contained in the air circulated through the test space.
2. Thus far, there have been no assurances that oxygen and carbon dioxide content in the test spaces have been kept under control.
3. There has been no correlation evident between outdoor and indoor environmental conditions.
4. Horizontal circulation by gravity through a test space of 1000 square feet (10 square feet per person) in the basement area of a building is marginal for producing an adequate number of air changes per hour. Also, there is no assurance that the quality of the circulating air will

be satisfactory for shelter occupancy. (Test #4, Building No. 1)

5. Inadequate natural air movement as demonstrated by an excessively high effective temperature existed under conditions of 10 square feet per person in the basement test space of a 5 story building when that space was connected to stair towers which were closed both to the outside air and to all corridors in the building. (Test #6, Building No. 3)
6. For a building with circulation limited to one story plus basement and occupancy of 15 square feet per person, more than 3 cfm per person air circulation by gravity occurred when the outlet openings were approximately 0.5 square feet per person and located near the top of the test space. However, effective temperature data was not reliable for this building configuration. (Test #3, Building No. 2)
7. A basement test space with approximately 10 square feet per person in a simulated 2 story building produced an air flow of approximately 10 to 12 cfm per person. However, the effective temperature approached 85 F within a 12 hour period, and equilibrium had not been reached. (Test #10, Building No. 3)
8. In a 5 story building, at a capacity of 10 square feet per person in the basement test space, air flows of approximately 10 to 12 cfm per person were obtained when stair towers were closed to the outside but opened to the top two floors and all interior doors of the dormitory

rooms on those floors were opened. However, an effective temperature of approximately 85 F was reached before equilibrium was established.

(Test #14, Building No. 3)

9. In a 5 story building, at a capacity of 15 square feet per person in the basement test space, air flows of approximately 12 to 13 cfm per person were attained when stair towers were closed to the outside but open to the top two floors and all interior doors of the dormitory rooms on those floors were opened. The effective temperature was 81 F after 104 hours of testing; however, equilibrium had not been reached due to continually changing external conditions. (Test #15, Building No. 3)
10. In a test space, with approximately 10 square feet per person in the basement of a 5 story building, air flows of 12 to 15 cfm per person were recorded. Interior doors to the stair towers were kept open at bottom and top levels. Effective temperatures were approximately 85 F and equilibrium had been reached. (Test #11, Building No. 3)
11. In a test space, with approximately 15 square feet per person in the basement of a 5 story building, air flows of 13 to 15 cfm per person were recorded. Interior doors to the stair towers were kept open at bottom and top levels. Effective temperatures were below 85 F and equilibrium had been reached. (Test #12, Building No. 3)

12. In a test space, with approximately 20 square feet per person in the basement of a 5 story building, air flows of 18 to 19 cfm per person were recorded. Stair towers were closed to the outside but open to the top floor and all interior doors of the dormitory rooms on that floor were opened. Effective temperatures were below 85 F and equilibrium had been reached. (Test #13, Building No. 3)
13. In a test space, with approximately 10 square feet per person in the basement of a 5 story building, air flows of 12 to 15 cfm per person were recorded. Stair towers were closed to the outside but open to the top two floors and all interior doors of dormitory rooms on those floors were opened. Also, a single window was open near the top of the leeward side of the building. Effective temperatures were below 85 F and equilibrium had been reached. (Test #16, Building No. 3)
14. With conditions similar to those described in 13 above, and an additional simulated occupancy of 50 (20 sq. ft./person) in a "side room" with a single entrance, air flows of 8 to 9 cfm per person were recorded in the "side room." The average effective temperature in both spaces was below 85 F. (Test #17, Building No. 3)
15. The work done thus far shows that under favorable conditions, basement spaces can be adequately ventilated by gravity alone

16. The results summarized above should be very useful as interim measures.

The work to date has provided a valuable insight into the phenomena and reliable measurement of natural air flow and the potential application for use in the identification of spaces not otherwise recognized as usable shelter. In addition, knowledge of potential natural ventilation greatly enhances the use of mechanically ventilated spaces in the event of power failure.

Much additional work needs to be done to develop generalized and reliable criteria for the use of natural ventilation in occupied shelter spaces in new and existing buildings. A suggested program, Recommendations for Further Study, is included in Appendix A.

APPENDIX A

RECOMMENDATIONS FOR FURTHER STUDY

A suggested program contains ten sub-tasks as follows:

TASK	TITLE	PAGE
P-1	Outside Infiltration Measurements -----	A-2
P-2	Building "Typing" for Natural Ventilation Potential ----	A-4
P-3	Reliable Measurement of Natural Ventilation -----	A-6
P-4	Natural Ventilation in Compartmented Spaces -----	A-7
P-5	Methods for Enhancing Natural Ventilation in Shelters -	A-8
P-6	Simple Mechanical Systems for Increasing Ventilation Rates in Natural Ventilated Shelter Spaces -----	A-9
P-7	Natural Ventilation in Upper Stories of Tall Buildings ---	A-10
P-8	Natural Ventilation in Low Buildings -----	A-11
P-9	Variation of Comfort Conditions and Significances of Temperature Gradient upon Optimum Utilization of Space in Shelters Ventilated by Natural Means -----	A-12
P-10	Use of Models in Evaluating Natural Ventilation of Shelters -----	A-14

TASK P-1 OUTSIDE INFILTRATION MEASUREMENTS

BACKGROUND

The use of natural circulation within a building to ventilate a shelter space depends on natural dissipation of heat, humidity, carbon dioxide and other products of living persons. The dissipation of these products from the building to the weather depends on a number of related factors. The factor to be studied specifically under this program is the tightness of the building walls and the magnitude of weather air infiltration.

OBJECTIVE

The objective of this task is to measure the air infiltration rate into a building space, to determine the dilution effect, and to evaluate this data in terms of the number of people that can be supported in a basement shelter space. The net volume of weather air entering the building must be equal to or greater than the volume of fresh air required in the shelter. Back flows as well as infiltration must be determined before net volume of fresh air can be ascertained.

PROCEDURE

1. Secure access to and operational control of a multi-story building having an internal volume of at least 250,000 cu. ft. or a ratio of 1000 cu. ft. per person sheltered.
2. Close the building doors and windows and secure all mechanical fans.
3. Open all interior doors and internal passages.

4. Instrument the building for determining the infiltration rate by a tracer gas decay method. This will require at least one sensing device on each floor.
5. Compute the infiltration rate for each floor and total the infiltration for the building.
6. Compare this total with the fresh air requirements for the test space.

TASK P-2 BUILDING "TYPING" FOR NATURAL VENTILATION

BACKGROUND

Observations made during this research project indicate that natural ventilation of shelter spaces is possible under certain conditions. Some of the factors which influence natural air flow include the type of building from several aspects: (1) the "infiltration" characteristics of the building and (2) the "engineered air flow pattern" which exists (coincidentally) because of normal arrangements of vertical ducts, stairs, elevators, and corridors. With the advent of air conditioning in the 1930's, modern buildings are being built without natural ventilation flow paths as a deliberate design of the building. If buildings are of appropriate type and coincidentally have an "engineered air flow pattern" their use for natural ventilated shelter is enhanced. Inasmuch as the infiltration characteristics and air flow paths are two important requirements for natural ventilation, it is desirable to establish a general "typing" of buildings for this purpose.

OBJECTIVES

1. Establish general criteria for potential naturally ventilated shelter systems in buildings.
2. Evolve a building "typing" system for use with natural ventilation criteria to quickly identify buildings having potential naturally ventilated shelter spaces.

PROCEDURE

1. Analyze experimental data from natural ventilation measurement project to further evaluate those characteristics of a building which enhance natural air flow patterns.
2. Conduct additional limited ventilation studies where necessary and feasible.
3. Evaluate magnitude in infiltration of typical buildings on basis of construction type, window and door types, walls, etc.
4. Explore and attempt to devise or adopt a building "typing" system useful for identification of order of magnitude of infiltration.
(e.g. a system as used in Boeckh's Manual of Appraisals may be a possible approach)
5. Explore and attempt to devise or adopt a building "typing" system for natural ventilation as related to vertical ducts, stairs, corridors, etc.
6. Explore computer "plan reading" and criteria program possibilities to improve the usefulness and standardization of a building "typing" system.

TASK P-3 RELIABLE MEASUREMENT OF NATURAL VENTILATION

BACKGROUND

Air change measurements which have been considered in various degrees of thoroughness have been subject to characteristics which tend to affect their accuracy. Humidity is notorious for its affect on electronic equipment. Some instruments are sensitive to variations in the moisture content of the air being sampled. Some instruments are limited in the distance between sensing devices and measuring equipment. Some techniques are tedious and time consuming where an instantaneous answer is desired.

OBJECTIVE

It is desired to develop an instrument which can be operated simply and with good reliability in a program which moves from building to building. Tracer gas decay methods have considerable promise and it is in this area that much of the effort will be directed.

PROCEDURE

1. The several methods which have been utilized in ventilation studies and any others that may have been developed recently will be studied for assets and limitations, including direct velocity measurement.
2. Selection of a method will be based on its promise to achieve the desired results, after planned modifications.
3. The modified system will be demonstrated under extremes of exposure.

TASK P-4 NATURAL VENTILATION IN COMPARTMENTED SPACES

BACKGROUND

On the basis of experimental work in the measurement of natural ventilation (Contract OCD-OS-62-64), data indicates that significant air flow can occur in compartmented spaces (i.e. "side rooms," adjacent to main air flow pattern). If an entire basement space is used for shelter purposes, flow of air in compartmented spaces becomes a matter of concern. In order to further analyze the "compartmentation problem," it is desirable to conduct a series of experiments in buildings having basement areas with compartments.

OBJECTIVE

1. To determine the natural ventilation in typical basement shelter spaces having compartments not in the line of direct air flow ("side rooms").

PROCEDURE

1. In the experimental test chamber and in specific basement test spaces, vary air flow and heat source configurations to determine factors influencing air flow patterns.
2. Establish "theoretical maximum occupancy" for typical "side rooms" located adjacent to principal air flow path.
3. Establish general guidelines to aid in predicting flow through typical basement spaces having "side rooms" of varying size and arrangement.

TASK P-5 METHODS FOR ENHANCING NATURAL VENTILATION IN SHELTERS

BACKGROUND

Observations made during this research project indicate that natural ventilation in shelter spaces can be enhanced by means of specific "deliberate openings" to the atmosphere. It is desirable to establish general guidelines for determining the influence of various "deliberate openings" considering air flow path in building, direction of prevailing winds, height of buildings, and area and location of openings.

OBJECTIVE

Establish general guidelines for determining the influence of "deliberate openings" on natural ventilation under various environmental conditions.

PROCEDURE

1. Under various environmental conditions evaluate experimentally the influence of the following factors upon natural ventilation.
 - a. Supplementary heat sources in outlet stacks
 - b. Area and location of "deliberate openings"
 - c. Direction and velocity of wind
 - d. Height of buildings
 - e. Air flow paths in buildings
2. Analyze experimental data in order to develop general guidelines for enhancing air flow through "deliberate openings."
3. Review typical building types to determine validity of usefulness of the "deliberate opening" concept.

TASK P-6 SIMPLE MECHANICAL SYSTEMS FOR INCREASING VENTILATION RATES IN NATURALLY VENTILATED SHELTER SPACES

BACKGROUND

During periods of minimum air circulation through shelter spaces, it may be necessary to supplement the natural air flow with mechanical air flow by means of a manually driven blower. The blower needs to be arranged so that several persons can provide the drive energy to move sufficient air to ventilate a space sheltering 50 or more persons.

OBJECTIVE

A high volume low static pressure fan or blower is to be designed and constructed to operate with one or two personnel.

PROCEDURE

1. Investigate information on fans and blowers to determine the combination which will yield the desired flow.

TASK P-7 NATURAL VENTILATION IN UPPER STORIES OF TALL BUILDINGS

BACKGROUND

Observations made during this research project indicate that natural ventilation of shelter spaces in basements is valid under certain conditions.

There are many cases where spaces in upper stories of tall buildings might be occupied for shelter reasons; hence, it is desirable to determine if natural ventilation for shelter in upper stories of tall buildings is possible and feasible under various closure conditions.

OBJECTIVE

Determine the feasibility of the use of natural ventilation in shelter spaces in upper stories of tall buildings.

PROCEDURE

1. Using typical full scale buildings, determine air change rates in test spaces in upper stories of tall buildings.
2. Determine ways to enhance the natural flow of air through test spaces in upper stories of tall buildings.
3. Determine influence of basement occupancy upon natural air flow in test spaces in tall buildings.
4. Develop guidelines to aid in the selection of potential upper story shelter spaces.

TASK P-8 NATURAL VENTILATION IN LOW BUILDINGS

BACKGROUND

Observations made during this research project indicate that natural ventilation of shelter spaces is valid for multi-story buildings under certain conditions. There exists, however, many basement shelter spaces not in multi-story buildings. It is feasible to determine ways of enhancing natural ventilation in basement spaces of single or two story buildings.

OBJECTIVE

Determine the feasibility of natural ventilation in basement spaces of typical single story or two story "institutional type" buildings.

PROCEDURE

1. By experiment, determine natural ventilation characteristics of typical single and two story "institutional buildings."
2. Determine ways to enhance the ventilation characteristics in basement spaces of single or two story buildings.
3. Establish guidelines to aid in the selection of basement spaces in single and two story buildings which might be feasible for use under natural ventilation conditions.

TASK P-9 VARIATION OF COMFORT CONDITIONS AND SIGNIFICANCE OF TEMPERATURE GRADIENT UPON OPTIMUM UTILIZATION OF SPACE IN SHELTERS VENTILATED BY NATURAL MEANS

BACKGROUND

In order for the principles of natural ventilation to work successfully in shelter spaces, there will be a variation of effective temperature from inlet to outlet. Specific full scale experiments conducted to date indicate differences between inlet and outlet temperatures of as much as 10 degrees F. Because of this variation, the utilization of the spaces as a shelter could be enhanced by careful arrangement of functions within the space. For example, sleeping functions might be placed at one end (cool end) and activity functions at the other end (warm end). In order to determine optimum space utilization in shelters having natural ventilation, two "kinds" of information must be developed.

1. A profile of effective temperature variation through the area of a naturally ventilated shelter under different characteristics of activity.
2. The influence of segregation of activity upon effective temperature variation throughout a shelter space.

Obviously each of these is interdependent and would have to be investigated concurrently.

OBJECTIVE

1. To determine effective temperature profile through typical occupied spaces (simulated occupancy) to be ventilated by natural means.

2. Investigate optimum arrangement (by activity) of interiors of spaces to be ventilated by natural means.

PROCEDURE

1. Theoretical analysis of utilization of typical spaces having effective temperature variations within the shelter.
2. Experimental study on limited basis of variation of effective temperature as a function of outdoor weather conditions, infiltration, air change rate, occupancy distribution, and occupancy activity.
3. Development of analog for evaluation of specific configurations, shelter sizes, air change rates, occupancy density, distribution, etc.
4. Development of typical optimum utilization and configuration studies to serve as guidelines for general use of shelter spaces ventilated by natural means.

TASK P-10 USE OF MODELS IN EVALUATING NATURAL VENTILATION OF SHELTERS

BACKGROUND

The problem of obtaining an entire multi-story building for ventilation studies, even for a two week period, has proved to an extremely difficult one.

It would be, therefore, of great value if a method could be devised whereby scale models, of the buildings in question, could be built and tested. This testing under environmentally controlled conditions could be carried out in climatometer facilities.

To date, very little has been done on solving the problems involved in scaling a building to a reasonable size.

OBJECTIVE

To determine the feasibility of using models to predict the natural flow of air through multi-story buildings.

PROCEDURE

1. Literature search for information on previous work done in the fields of model testing.
2. A mathematical analysis of the physical parameters involved. The aim is to develop a series of dimensionless numbers that would govern the scaling such as the Reynold's number does in airplane design testing.

3. Construction of a test model using the parameters obtained in Step 2.
4. Laboratory testing of the model in climatometer facilities using several weather conditions.
5. Use of the IBM 7074 in the calculation, comparison and evaluation of data taken.
6. Interpretation of results and comparison with data previously obtained under actual conditions.
7. Decision of the feasibility of using models and their limitations.

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